MODELING OF TEMPERING OF FROZEN POTATO PUREE BY MICROWAVE, INFRARED ASSISTED MICROWAVE AND OHMIC HEATING METHODS

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ABSTRACT

MODELING OF TEMPERING OF FROZEN POTATO PUREE BY MICROWAVE, INFRARED ASSISTED MICROWAVE AND OHMIC HEATING METHODS

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The main purpose of this thesis is to develop a model that can predict the temperature profile inside a frozen food sample during microwave tempering and infrared assisted microwave tempering processes. Another goal of the study is to compare the tempering time of frozen foods by using microwave, infrared assisted microwave, and ohmic heating methods. Frozen potato puree was used as the food sample for all studies.

Three different microwave power levels (30%, 40%, and 50%) were used for microwave tempering studies. Three different microwave power levels (30%, 40%, and 50%) and three different infrared power levels (10%, 20%, and 30%) were combined for infrared assisted microwave tempering. As a control, tempering was done by keeping the sample at 4°C. The increase in microwave power level and infrared power level reduced tempering time in infrared assisted microwave tempering. For the ohmic tempering studies, three different frequencies (10 kHz, 20 kHz, and 30 kHz) and three different salt contents (0.50%, 0.75%, and 1.00%) were used. The increase in frequency of ohmic heating and salt content also decreased tempering times.

Microwave tempering and infrared assisted microwave tempering of frozen foods were simulated by using finite difference method. For this purpose, the change in heat capacity and the dielectric properties of frozen potato puree with respect to time were measured. The temperature distribution inside the sample was modeled, and the predicted results were compared with experimental results. The predicted temperatures showed good agreement with the experimental data ($r^2 \geq 0.985$). It was possible to decrease tempering times by about 75%, 90%, and 95% using ohmic, microwave, and infrared assisted microwave tempering methods, respectively as compared to control.

Keywords: microwave, infrared, ohmic, tempering, modeling

ÖZ

DONDURULMUŞ PATATES PÜRESİNİN MİKRODALGA, KIZILÖTESİ DESTEKLİ MİKRODALGA VE OHMİK ISITMA YÖNTEMLERİ İLE ÇÖZDÜRÜLMESİNİN MODELLENMESİ

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Bu tezin ana amacı, mikrodalga ve kızılötesi destekli mikrodalga yöntemleri ile sırasında dondurulmuş gıda örneğinin içindeki sıcaklık dağılımını tahmin edecek bir model geliştirmektir. Çalışmanın bir diğer amacı, dondurulmuş gıdaların mikrodalga, kızılötesi destekli mikrodalga, ve ohmik ısıtma yöntemleri ile çözdürülme sürelerinin karşılaştırılmasıdır. Tüm çalışmalarda gıda örneği olarak dondurulmuş patates püresi kullanılmıştır.

Mikrodalga ile çözdürme çalışmaları için üç farklı mikrodalga güç seviyesi (%30, %40, ve %50) kullanılmıştır. Kızılötesi destekli mikrodalga ile çözdürme çalışmaları için üç farklı mikrodalga güç seviyesi (%30, %40, ve %50) ile üç farklı kızılötesi güç seviyesinin (%10, %20, ve %30) kombinasyonları kullanılmıştır. Kontrol olarak örnek 4°C'de bekletilerek çözdürülmüştür. Mikrodalga ve kızılötesi güç seviyelerindeki artış çözdürme süresini kısaltmıştır. Ohmik çözdürme yöntemi ile yapılan çalışmalarda üç farklı frekans (10 kHz, 20 kHz, ve 30 kHz) ve üç farklı tuz konsantrasyonu (%0.50, %0.75, ve %1.00) kullanılmıştır. Frekans ve tuz konsantrasyonundaki artış da çözdürme süresini kısaltmıştır.

Dondurulmuş gıdaların mikrodalga ve kızılötesi destekli mikrodalga yöntemleri ile çözdürülmesi sonlu fark yöntemi kullanılarak modellenmiştir. Bu amaçla dondurulmuş patates püresinin ısı kapasitesi ve dielektrik özelliklerinin zamana göre değişimi ölçülmüştür. Örneğin içindeki ısı dağılımı modellenmiş ve tahmin edilen sıcaklıklar deneysel sonuçlarla karşılaştırılmıştır. Tahmin edilen sonuçlar deneysel veriler ile iyi uyum göstermiştir ($r^2 \geq 0,985$). Ohmik, mikrodalga, ve kızılötesi destekli mikrodalga yöntemleri kullanıldığında çözdürme sürelerini kontrole göre sırasıyla %75, %90, ve %95 azaltmak mümkün olmuştur.

Anahtar Kelimeler: mikrodalga, kızılötesi, ohmik, çözdürme, modelleme

Dedicated to my mother, for her unlimited and unconditional love…

◆

Anneme, sınırsız ve koşulsuz sevgisi için…

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A: cross-sectional surface area (cm^2)

C_p: heat capacity (J/kg. °C)

D: diameter (cm)

D_p: penetration depth

h: heat transfer coefficient ($W/m^2.°C$)

I: current (ampere)

k: thermal conductivity (W/m.°C)

L: height (cm)

m: weight (kg)

Q: heat absorption (W/m^3)

R: resistance (ohm)

T: temperature (°C)

t: time (s)

V: voltage (Volt)

Greek symbols:

ε': dielectric constant

ε'': dielectric loss factor

ρ: density (kg/m^3)

σ: electrical conductivity (Siemens/m)

∂: partial derivative

λ_0: wavelength of microwave energy in free space (cm)

CHAPTER 1

INTRODUCTION

1.1 Microwave Heating

Wavelength or frequency classifies electromagnetic radiation. Microwaves represent the electromagnetic spectrum between frequencies of 300 MHz and 300 GHz. The frequency of microwaves lies between the radio frequencies and infrared (Figure 1.1). Since microwave frequencies are close to radio frequencies and can overlap radar range, their use is regulated by the Federal Communications Commission. Approved microwave frequencies for food use are 2450 and 915 MHz (Giese, 1992). Microwave ovens manufactured today for home and commercial use usually operate at 2450 MHz. Some industrial microwave ovens operate at 915 MHz.

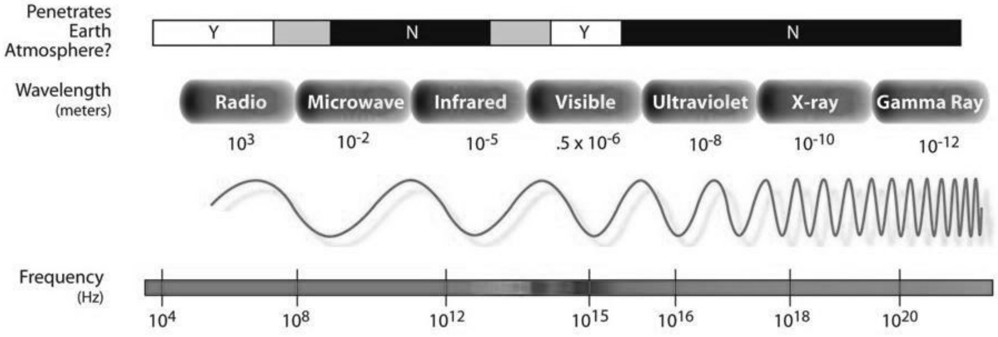

Figure 1.1 The electromagnetic spectrum

Microwaves are usually generated by an electronic device, called magnetron. The magnetron is a device that converts electrical energy at low frequencies into an electromagnetic field with centers of positive and negative charge that change direction billions of times each second. This device is enclosed within a metal box or oven cavity (Giese, 1992).

Microwaves can be absorbed, transmitted and reflected. They can be transmitted through glass, ceramics, plastics, and paper without any absorption or reflection. Metals such as aluminum foil and steel reflect microwaves. Some materials, however, are only partially transparent to microwaves (Giese, 1992). When a material absorbs microwaves, the microwave energy is converted into heat. The properties of a material determine the amount of microwaves absorbed, reflected, and/or transmitted (Schaefer, 1999).

The absorption of microwaves by a material results in the microwaves giving up their energy to the material. This transfer of energy causes the temperature of the material to rise (Schaefer, 1999). There are two heating mechanisms for microwave processing: ionic conduction and dipolar rotation (Figure 1.2). In a microwave oven, magnetron produces an alternating electric field in the oven cavity. In ionic interaction mechanism, any charged particle found in the oven experiences a force alternating at the rate of microwave frequency. The net force will first accelerate the particle in one direction and then in the opposite, with particles of opposite charges being accelerated in opposite directions. If the accelerating particle collides with an adjacent particle, it will impart kinetic energy to it and set it into more agitated motion than it previously had. Since heat is defined as the agitation of particles or molecules, the particle's temperature increases due to agitation. As agitated particle interacts with its neighbors, it transfers heat to them until all neighboring particles have had their temperatures increased. Heat is then transferred to the other parts of the material (Buffler, 1993).

Dipolar rotation mechanism depends on the existence of polar molecules. Water, which is the major component of most foods, is the most common polar molecule. Under normal conditions, polar molecules are randomly oriented. In the presence of an electric field, polar molecules tend to orient themselves in the initial field direction. As they do, they collide randomly with their neighbors. Since microwave field is reversing its polarity at the rate of microwave frequency, polar molecules attempt to align themselves with the changing field, so further collisions occur. Heat is generated as a result of the rotation of the molecules. In doing so, a considerable kinetic energy is extracted from microwave field and heating occurs (Buffler, 1993; Decareau & Peterson, 1986).

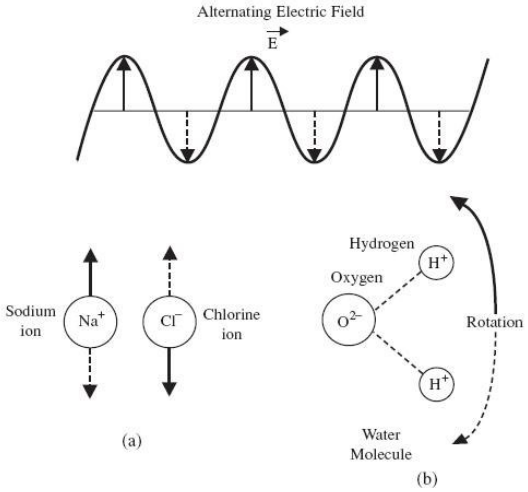

Figure 1.2 Mechanisms of microwave interaction with food: (a) ionic conduction (b) dipolar rotation (Sahin & Sumnu, 2006)

The heating mechanisms of microwave heating and conventional heating are different. In microwave-heated foods, time-temperature profiles within the product are mainly caused by internal heat generation due to absorption of electrical energy from the microwave field, and then heat is transferred by conduction, convection, and evaporation (Mudgett, 1982). The ambient temperature in a microwave oven rarely reaches much above the room temperature. Therefore, evaporative cooling occurs at the surface of the food, and this results in a negative temperature gradient; that is a lower surface temperature than the interior parts of the microwave heated food (Decareau, 1992). In conventional heating, heating results from a combination of three basic energy transfer mechanisms, conduction, convection, and radiation. In this case, heat is transferred from the surface to the interior (Yin & Walker, 1995).

Compared to conventional heating, moisture flow due to concentration and pressure gradients are uniquely and significantly altered during microwave heating (Datta, 1990). When a food material is heated in a microwave oven, moisture evaporates inside the food, migrates within the food, and eventually moves out through the surface. Relatively larger amounts of interior heating result in increased moisture vapor generation inside of a solid food material, which creates significant interior pressure and concentration gradients. Positive pressures generated inside of a food material increase the flow of the vapor and liquid through the food material to the boundary (Datta, 1990).

Use of microwave heating has a lot of advantages such as less start up time, faster heating, energy efficiency, space savings, precise process control, selective heating and food with high nutritional quality (Decareau & Peterson, 1986). Speed of operation is the primary advantage of microwave processing. Since microwaves penetrate within a food and do not retain just at the surface, heating occurs more rapidly and efficiently. Microwave processing can also be helpful to control energy costs, since heating takes place only in the food material being processed, not in the surrounding medium (Giese, 1992). Drawbacks of microwave heating are its inability to brown food, non-uniform heating, excessive drying of foods such as breads, and runaway heating.

1.1.1 Importance of Food Properties in Microwave Heating

The important food properties that affect microwave heating are electrical properties of the food, thermal properties of the food, density, size, and shape of the food. The microwave heating characteristics of food materials are also dependent on the frequency and power of the microwave oven.

1.1.1.1 Electrical Properties of the Food

Microwaves interact with materials based on their electrical properties. Electrical properties involve dielectric properties (dielectric constant and dielectric loss factor) and penetration depth. The dielectric properties of a food are characteristics of the materials determining the interaction of electromagnetic energy with the materials, so they play a major role in microwave heating. Dielectric constant (ε′) is a measure of the ability of a food material to store electrical energy (Mudgett, 1986; Giese, 1992). Dielectric loss factor (ε″) is the ability of a food material to dissipate electrical energy into heat (Mudgett, 1982). Foods with high dielectric loss factors are called as lossy materials, and these foods are heated more rapidly by microwaves (Owusu-Ansah, 1991; Giese, 1992). Generally, the dielectric properties of a food are dependent on temperature, frequency, bulk density, moisture content and chemical composition of the food (Calay *et al.*, 1995).

Heating due to microwave radiation depends on the penetrating power of the microwaves (Owusu-Ansah, 1991). Owing to this, penetration depth (D_p) becomes a very important parameter for microwave heating. Penetration depth is defined as the distance from the surface of the material at which the microwave power decreases to 1/e (~37%) of its original value. Penetration depth increases with decreasing frequency (Metaxas & Meredith, 1983). Penetration depth is also controlled by the dielectric properties. It is defined as:

$$D_p = \frac{\lambda_0}{2\pi\left(2\varepsilon'\right)^{0.5}}\left\{\left[1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2\right]^{0.5}-1\right\}^{-0.5} \tag{1}$$

where D_p is penetration depth (cm), λ_0 is the wavelength of the microwave energy in free space (32.76 cm at 915 MHz and 12.24 cm at 2450 MHz), ε' is dielectric constant and ε'' is dielectric loss factor (Von Hippel, 1954).

The relative magnitudes of penetration depth and sample size determine the uniformity of heating. If the penetration depth is much larger than the sample size, there will be little variation in the rate of heat from the surface to the interior of food and the resulting heating will be uniform (Datta, 1990). When the penetration depth is less than the sample size, non-uniform heating and more surface heating take place, and runaway heating can be seen (Schiffmann, 1993).

The measurement of dielectric properties in microwave frequencies can be done by using waveguide and coaxial transmission line method, open-ended probe method, and cavity perturbation method. Generally, measurement techniques can be categorized into reflection or transmission measurements by resonant or non-resonant systems, with open or closed structures for measuring the dielectric property of the material (Kraszewski, 1980).

1.1.1.2 Thermal Properties of the Food

Specific heat and thermal conductivity are the important thermal properties for microwave heating. Specific heat of food determines how fast a food can be heated. Specific heat is often a neglected parameter in microwave heating, but it should have an overriding effect especially for foods having low loss factors such as fats and oils. Specific heat is the property that can cause a food material with a low loss factor to be heated well in the microwave field. It was shown that for sufficiently large and thick samples, oil might be heated faster than water of the same mass. However, the trend is not true in smaller samples (Barringer *et al.*, 1994). Controlling specific heat can be a powerful tool in formulating microwavable foods (Schiffmann, 1986).

Thermal conductivity is a measure of a material's ability to transfer heat in response to a temperature difference. Thermal conductivity plays less role in microwave heating than conventional heating due to the very short heating times (Schiffmann, 1993). High thermal conductivity materials dissipate heat faster than low thermal conductivity materials during microwave heating. Food with high thermal conductivity will take less time to attain uniform temperature during holding period (Gunasekaran, 2002).

1.1.1.3 Size, Shape, and Density of the Food

The physical geometry, i.e. the size and shape of the food is also important for microwave heating. Size of the food should be chosen with respect to the penetration depth in order to obtain uniform heating. Shape of the food items is a considerable parameter. Sphere is the ideal shape since energy tends to be focused to give heating at or toward the center of the sphere. Cylinder is the next best shape in terms of heating performance (Decareau, 1992). The more regular the shape, the more uniform the heating. Sharp edges and corners should be avoided since they will tend to overheat (Schiffmann, 1986).

The bulk density of a product has an effect upon its dielectric properties. As material's bulk density increases, its dielectric constant and loss factor also increase, often in a linear fashion (Schiffmann, 1986).

1.2 Infrared Heating

Infrared (IR) radiation is the part of the sun's electromagnetic spectrum that is predominantly responsible for the heating effect of the sun (Ranjan *et al*., 2002). The frequency of infrared radiation lies between microwaves and visible light (Figure 1.1). Thermal infrared radiation is generally considered to be in the range of 0.1–100 μm and is typically divided into near-infrared radiation (NIR) (0.75–3 μm), mid-infrared radiation (MIR) (3–25 μm), and far-infrared radiation (FIR) (25–100 μm). Infrared heating is important in many common food processing operations such as baking, roasting, blanching, and surface pasteurization, due to its intense heating (high heat flux) capability and small penetration depth (Almeida, Torrance & Datta, 2006).

A ceramic rod (the most commonly used infrared source) and a halogen source emit infrared radiation in different wavelength ranges. A portion of the emissive power of halogen lamps is in the visible light range, which is why the halogen (near-infrared) heating mode is sometimes referred to as "light" heat. As penetration of infrared radiation is poor, the heating effect of infrared radiation has an impact only on the surface of the body and heat transfer through the body proceeds by conduction or convection (Sepulveda & Barbosa-Canovas, 2003). The penetration depth of infrared radiation has a strong influence on how much the surface temperature increases or the level of surface moisture that builds up over time. Infrared radiation penetration depths can vary significantly for various food materials. Datta & Ni (2002) showed that as the infrared radiation penetration depth decreases, the surface temperature increases.

Some of the advantages of infrared radiation as compared to conventional heating are reduced heating time, equipment compactness, rapid processing, decreased chance of flavor loss, preservation of vitamins in food products, and absence of solute migration from inner to outer regions (Ranjan *et al.*, 2002).

Infrared heating has been used for several purposes in food industry (Nowak & Lewicki, 2004; Hashimoto *et al.*, 1992). Nowak & Lewicki (2004) used near-infrared radiation to dry apple slices and compared infrared drying with conventional drying. They claimed that drying of thin layers seemed to be more efficient at far-infrared radiation, while drying of thicker bodies should give better results at near-infrared radiation. Hashimoto *et al.* (1992) studied the influence of far-infrared irradiation on pasteurization of *E. coli* and *S. aureus* on or within a model for wet-solid food.

1.3 Combination of Infrared and Microwave Heating

Combination heating implies two different heating mechanisms together. Figure 1.3 shows an example of microwave-infrared combination oven. The main purpose of using infrared heating in the same cavity as of the microwave heating is to assist microwave heating in terms of reaching a more homogeneous temperature distribution on the target food and drying up the accumulated moisture due to the pressure driven moisture flow (Ni *et al.*, 1999). There are a few studies on infrared-microwave combination heating of foods (Datta & Ni, 2002; Keskin *et al.*, 2004;

Tireki *et al*., 2006, Wang & Sheng, 2006; Sakiyan *et al*., 2007). Datta & Ni (2002) analyzed infrared and hot-air-assisted microwave heating of foods. Wang & Sheng (2006) dried peach by using far-infrared heating combined with microwave drying. Tireki *et al.* (2006) used infrared-assisted microwave drying for production of bread crumbs and determined drying conditions in infrared-microwave combination oven to produce bread crumbs with the highest quality. Keskin *et al*. (2004) and Sakiyan *et al*. (2007) both used infrared-microwave combination heating for baking purposes.

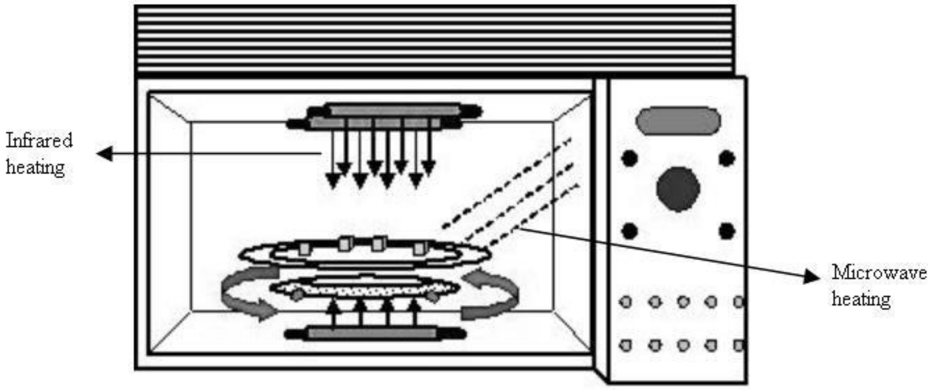

Figure 1.3 Microwave-infrared combination oven

1.4 Ohmic Heating

Ohmic heating provides a new heating method and a new inspecting technology for food processing. Ohmic heating is named after the Ohm's Law (Equation 2).

$$V = I \times R \tag{2}$$

where V is voltage (V), I is current (amp), and R is electrical resistance (ohm). Ohmic heating is based on the passage of alternating electrical current through a food product that serves as an electrical resistance (Reznick, 1996). Due to the current passing through the food sample, relatively rapid heating occurs.

The advantages of ohmic heating are shorter heating time, easy process control, relatively uniform heating and high energy conversion efficiency. Ohmic heating has good energy efficiency since almost all of the electrical power supplied is transformed into heat.

In ohmic heating, the current passing through the food results in sudden heat generation. Volumetric heating occurs, and the temperature distribution is homogenous. A temperature difference of 55ºC can be obtained in less than one second (Reznick, 1996).

In practice, heating can be done by applying alternating current at low frequencies (50 or 60 Hz). Therefore, power supplier is simple and cheap. Also this low frequency interval is the region that the possibility of formation of electrochemical reactions is the lowest for the food materials (Tempest, 1995). But low frequencies have an electrolytic effect similar to that of direct current. The major electrolytic effect is the dissolution of the metallic electrodes, which may contaminate the product (Reznick, 1996). To overcome this problem, high frequencies can be used.

As compared to microwave heating, ohmic heating is more efficient because nearly all of the energy enters the food since heat and ohmic heating has no limitation of penetration depth. Although microwave heating requires no physical contact, ohmic heating requires electrodes in good contact with the food (Li & Sun, 2002).

Many factors affect the heating rate of foods undergoing ohmic heating: electrical conductivities of fluid and particles, the product formulation, specific heat, particle size, shape and concentration as well as particle orientation in the electric field (Kim *et al.,* 1996). Conductivity differences between the particulates and the carrier medium should be minimized to achieve evenness of heating (Zoltai & Swearingen, 1996). When particulates and the carrier medium have comparable conductivities, the temperature rise will depend on the specific heat capacities.

Moreover, the location of the solid phase within the ohmic heating cell in terms of series or parallel position or well mixed situation with liquid phase is another important subject to be considered (Zareifard *et al.*, 2003). Sastry (1991) noted that particle concentration is a critical factor in determining the heating rate of the two phases.

The most important food property when applying ohmic heating is the electrical resistance or the electrical conductivity of the food product. In highly conductive materials such as metals, a large current will flow. In highly resistive materials like woods, there will be negligible current. Pure fats, oils, alcohols and sugars are not suitable for ohmic heating since these substances are electrically too resistive. In general, solids exhibit lower electrical conductivities than liquids. Electrical conductivity depends also on temperature. Ohmic heating rates are critically dependent on electrical conductivity of the food being processed (Zoltai & Swearingen, 1996).

Devices have been developed to measure the electrical conductivities of food particles for various geometries since it was not easy to find commercial meters (Mizrahi *et al.*, 1975; Mitchell & de Alwis, 1989). Practically, electrical conductivity (σ) of the food product is calculated using the following equation adapted from Palaniappan & Sastry (1991):

$$\sigma = \left(\frac{1}{R}\right) \times \left(\frac{L}{A}\right) \times 100 \tag{3}$$

where L is the gap between the electrodes (cm), A is the cross-sectional surface area of the electrodes (cm^2), and R is the resistance of the product (ohm). The ratio of L/A is known as the cell constant of the ohmic heating unit. R can be determined from voltage (V) and current (I) data:

$$R = \frac{V}{I} \tag{4}$$

Ohmic heating has been used in food industry for several purposes (Marcotte *et al.*, 1998; Lima & Sastry, 1999; Sensoy & Sastry, 2003; Zareifard *et al.*, 2003; Piette *et al.*, 2004). Marcotte *et al.* (1998) studied the ohmic heating behavior of hydrocolloid solutions. Lima & Sastry (1999) searched the effects of ohmic heating frequency on hot-air drying rate and juice yield for ohmic pretreatment of fruits and vegetables. Sensoy & Sastry (2003) blanched mushrooms by ohmic heating. Zareifard *et al.* (2003) studied the ohmic heating behavior and electrical conductivity of two-phase food systems. Piette *et al.* (2004) investigated the effect of ohmic cooking on the quality of processed meats.

1.5 Thawing and Tempering

Freezing preservation of food has been used for thousands of years because foods with high product quality can be obtained by freezing (Persson & Londahl, 1993). Freezing temperatures reduce the activity of microorganisms and enzymes. Thawing is considered to be the reverse process of freezing, except for the different thermal properties of water and ice. Water has a higher heat capacity and lower thermal conductivity than ice, hence, for an identical driving force, the thawing time will be longer than the freezing time (Delgado & Sun, 2001). During thawing, foods are subjected to damage by chemical, physical, and microbiological changes. Quick thawing at low temperatures to avoid remarkably rise in temperature and excessive dehydration of food is desirable so as to assure food quality (Li & Sun, 2002).

Thawing of frozen foods is an important unit process in the food industry because the industry relies heavily on large quantities of food that have been preserved by freezing for use throughout the year. Hendricks *et al.* (1988) reported that in the past freezing had been more important than thawing, but due to greater quantities of frozen foods receiving further processing by manufacturers, thawing was gaining more industrial interest. The most common thawing method is to apply heat to the surface of the frozen food and to allow the heat to be conducted to the interior. Since the heat is applied to the surface, it must travel through the surface to reach the interior. Thermal conductivity of frozen foods is almost three times that of non-frozen foods. Surface thaws first and has lower thermal conductivity than the frozen interior and cannot transfer adequate heat to the interior without increasing the temperature of the thawing surface to undesirable levels (Schaefer, 1999). The result of this is long thawing cycles that are often characterized by unacceptable changes in product quality. The disadvantages of conventional thawing are long processing times, large space requirements, and increased risk of chemical and biological deterioration of the food product (Li & Sun, 2002).

Frozen food is defined as `tempered' when its temperature is raised from that of a frozen condition to some higher temperature, still below the initial freezing point, at which it is still firm but can readily be further processed (James, 1999). Thawing is usually regarded as complete when the center of the food sample has reached 0°C. Lower temperatures (e.g. -5 to -2°C) are acceptable for food that is destined for further processing, but such food is tempered rather than thawed. The two processes should not be confused because tempering only constitutes the initial phase of a complete thawing process (James & James, 2002).

Rapid thawing has been of interest because uncontrolled slow thawing rate can negate the high quality of a food product achieved by controlled rapid freezing and cold storage (Clements, 2006). Volumetric heating methods offer solutions to thawing problems. Volumetric heating does not require large amounts of water, and it is more rapid since the thermal conductivity of the food product does not control the thawing rate (Clements, 2006).

1.5.1 Microwave Thawing and Tempering

The unique property of microwaves to penetrate and produce heat deep within food materials make them potential in accelerating thawing (Tong *et al*., 1993). Microwave thawing requires shorter thawing time and smaller space for processing, and reduces drip loss, microbial problems and chemical deterioration. However, runaway heating has limited the application of microwave thawing to food systems (Li & Sun, 2002). Thawing foods with microwave energy is difficult because of the significant difference between dielectric properties of ice and water. Table 1.1 shows that ice has significantly lower dielectric properties when compared to water (Schiffman, 1986).

Table 1.1 Dielectric properties of water and ice at 2450 MHz

	Dielectric constant (ε´)	**Dielectric loss constant (ε´´)**
Ice	3.2	0.0029
Water (at 25ºC)	78	12.48

Because of its low dielectric loss factor, ice is more transparent to microwaves than water and therefore water heats up much more rapidly when exposed to microwaves than ice. If the food product has frozen and unfrozen portions, then the product will experience runaway heating. If the temperature of a portion of the food product is allowed to rise above its freezing point, the temperature of this portion will rise much faster than the surrounding frozen portions and runaway heating will occur. Runaway heating is obviously related to temperature variation within the food product; therefore, by avoiding a large temperature variation within the food product during microwave tempering, runaway heating can be reduced and hopefully eliminated. So, all portions of the frozen food product should be maintained at a temperature just below the freezing point throughout microwave tempering process. This also reduces the non-uniform heat distribution within the food product (Schaefer, 1999).

The thawing rates in microwave thawing depend on food properties, dimensions, and the frequency. Factors like thermal properties varying with temperature, irregular shapes, and heterogeneity of the food make the thawing process more complicated (Taoukis *et al.*, 1987).

Meisel (1972) studied microwave thawing of lamb and pork, and recognized that microwave penetration from the surface at 2450 MHz decreased rapidly as the product temperature approached to 0°C. This makes it almost impossible to keep surface temperature of the product low and thaw the core of the product. Meisel (1972) found that it was difficult to obtain core temperatures higher than -3°C without overheating the surface. This brought on the idea of microwave tempering as opposed to microwave thawing. Microwave tempering is defined as raising the temperature of a frozen product from frozen storage temperature to temperature slightly below the product's freezing point (Schaefer, 1999). The penetration depth of microwave energy decreases as temperature of the frozen product increases. Substantially less energy is required if the tempering is terminated at a lower temperature.

Microwave tempering rather than complete thawing makes sense because in most cases complete thawing is not necessary since it is a waste of energy, it affects quality, and increases processing time. Microwave tempering has several advantages over most thawing processes (Schaefer, 1999). Microwave tempering process can handle large amounts of frozen product at small cost, has a high yield, and is accomplished in small spaces with no bacterial growth (Meisel, 1972).

Thawing and tempering of frozen materials are important in food processing since freezing is a convenient way of preserving food. Conventional thawing is a long process and can often compromise the product quality. Microwave thawing is a novel method having the advantages of fast heating rate, improved bacterial control and low costs. Minimizing thawing times will reduce microbial growth, chemical deterioration and excessive water loss caused by dripping or dehydration (Taher & Farid, 2001).

Since microwave-infrared combination heating is a very new technology, there is no study in literature on infrared assisted microwave thawing or tempering.

1.5.2 Ohmic Thawing and Tempering

Ohmic thawing uses the electrical resistance of a frozen food product to generate the heat volumetrically within the food product itself, as an electrical current is passed through the food product (Clements, 2006). Using ohmic heating to thaw frozen foods is an innovative method. Ohtsuki (1991, 1993) patented an ohmic thawing process where frozen foods positioned with negative electrons were introduced into a high voltage electrostatic field. Using this method, frozen foodstuffs can be thawed rapidly in the temperature range of -3 to 3°C. For instance, the thawing time for frozen tuna, beef and eggs was shortened to 1/4–1/3 of that of conventional thawing under the same temperature condition (Li & Sun, 2002). Yun *et al*. (1998) examined ohmic thawing of frozen chucks of meat in combination with conventional water immersion thawing, and they found that ohmically thawed samples showed reduced drip loss and improved water holding capacity when lower voltages were applied.

The advantages of ohmic thawing are shorter thawing time, easy process control, relatively uniform heating, no water used in the process and no waste water generated and high energy conversion efficiency (Roberts *et al*., 1998). But satisfactory performance of this method is dependent on assuring a good contact between the electrodes and product. Oddly shaped products may present a practical problem in achieving such a good contact (Naveh *et al*., 1983).

There are several studies on ohmic thawing (Naveh *et al*., 1983; Henderson, 1993; Roberts *et al*., 1998). Naveh *et al*. (1983) immersed the frozen product in a liquid and used electroconductive heating to thaw the sample by positioning between two electrodes having no direct contact with the sample, and they concluded that electroconductive thawing was a rapid thawing method. Henderson (1993) used ohmic heating to thaw shrimp blocks and found that as the frozen product thaws, current passes through the thawed portion of the block more readily, following a path of the least resistance. Roberts *et al*. (1998) designed and tested an automated, computer controlled prototype ohmic thawing unit, and the performance was tested with shrimp blocks. They concluded that ohmic thawing did not use any water, or generate much wastewater, and was more energy efficient. Moreover, the test results proved that the time for ohmic thawing was comparable to time for water immersion thawing, without the incidence of hot spots.

1.6 Modeling

Modeling represents a phenomenon using set of mathematical equations. The solutions to these equations are supposed to simulate the natural behavior of the material. Modeling can be a design tool to develop a food that will provide optimum heating results in the microwave oven. In the modeling work, the food system is represented as being made up of many small elements in the simulation process. These discrete elements are joined together to make up the product (Lorenson, 1990).

The particular element when modeling heat transfer of a food material is the temperature distribution. An accurate model can provide the temperature distribution at any time during the heat transfer process by solving the fundamental heat transfer equations. Properties of the food material such as density, specific heat, thermal conductivity, and electrical properties are included in the fundamental equations. For accurate modeling, the values of these properties must be known. When these values are dependent on temperature, equations become more complex. For these situations, numerical methods are employed.

Numerical methods provide approximate solutions to the equation at a finite number of points. The study of numerical methods for the solution of differential equations is complex, in part, because it runs counter to the usual pattern of moving from the discrete to the continuous. Numerical methods, in brief, replace a differential description of a physical process or system with an approximate discrete analog and then solve this analog to represent the solution of the differential system. The analog should approximate the differential equation with a known and tolerable degree of accuracy.

A fundamental principle of numerical methods is the reduction of a differential equation to an approximation in terms of algebraic equations. This reduction replace a continuous differential equation, whose solution space is generally infinite dimensional, with a finite set of algebraic equations whose solution space is finite dimensional. One avenue by which this reduction can be achieved is the finite difference method.

In broad outline form, the finite difference method proceeds by first identifying a finite number of discrete points within the domain of interest. These points are called nodes, and at these points approximations to the true solution are computed. Definition of the node locations is called the discretization step. Next the derivatives that appear in the differential equation are replaced by discrete difference approximations. These approximations are written in terms of nodal equations of the unknown function. This step, called the approximation step, produces a set of algebraic equations with described nodal values as unknowns. If the original differential operator is linear, the resulting algebraic system is also linear; otherwise the algebraic equations may be nonlinear. The final step follows the approximation step and involves solution of the resulting algebraic system of equations. Upon completion of this step, a discrete approximation to the solution of the original differential equation is obtained.

There are several studies on modeling of microwave thawing in literature (Chamchong & Datta, 1999a, 1999b; Taher & Farid, 2001; Liu *et al.*, 2005). Chamchong & Datta (1999a, 1999b) studied the effects of power levels and power cycling, and effect of load geometry and dielectric properties during thawing of foods in a microwave oven. They used tylose, a common food analog, as the sample for their experiments. They developed a model for temperature profile during thawing of tylose by using finite element method. The 3-D governing equation they used for heat transfer in a brick geometry with microwaves from x and y directions was:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + Q - I \tag{5}$$

where the heat generation term *Q* was given by:

$$Q = \frac{F}{\delta_x}\left[\exp\left(-\int_{-L_1/2}^{x}\frac{dx}{\delta_x}\right) + \exp\left(-\int_{x}^{L_1/2}\frac{dx}{\delta_x}\right)\right] + \frac{F}{\delta_y}\left[\exp\left(-\int_{-L_1/2}^{y}\frac{dy}{\delta_y}\right) + \exp\left(-\int_{y}^{L_1/2}\frac{dy}{\delta_y}\right)\right] \tag{6}$$

where δ_x and δ_y are the penetration depths in x and y directions, respectively. The evaporation term I was assumed as:

$$I = \begin{cases} 0 & when \quad T < 100°C \\ Q & when \quad T > 100°C \end{cases} \tag{7}$$

Taher & Farid (2001) investigated microwave thawing of frozen minced beef samples both experimentally and theoretically. Their model was based on a moving boundary model, and the thawing time was found to be less than one-fifth of that required in conventional thawing. They used one-dimensional unsteady state heat conduction equation with heat generation to describe microwave heating of material undergoing thawing:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + Q_y \tag{8}$$

where Q_y is the microwave energy absorbed at the different locations in the sample, which is commonly related to the microwave surface absorption Q_0 defined as follows:

$$Q(y) = Q_0 e^{-(y/D_p)} \tag{9}$$

where D_p is defined as:

$$D_p = \frac{c}{2\pi f}\left(0.5K'\left(\sqrt{1+\left(\frac{K''}{K'}\right)^2}-1\right)\right)^{-1/2} \qquad (10)$$

where c is speed of light (m/s), f is frequency, K′ is relative dielectric constant, and K″ is relative dielectric loss.

Liu *et al*. (2005) simulated the power and temperature distribution during microwave thawing by using Maxwell's equations and Lambert's law. Their experimental material was frozen tuna containing 75% water. They also used the one-dimensional heat transfer equation with a term for internal heat generation as follows:

$$\rho Cp\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) + P(z) \qquad (11)$$

where *P(z)* is the microwave power absorbed per unit volume. They concluded that although Lambert's law is theoretically less applicable for simulating the transmitted microwave power, it provided an effective numerical approach for calculating temperature distribution during microwave thawing, which proved compatible with experimental results.

1.7 Aim of the Study

Among preservation methods, freezing is very popular since it has the advantages of maintaining high product quality and extending the shelf life of foods. Thawing and tempering become very important to preserve product quality. However, chemical, physical, and microbiological changes that occur during long thawing and tempering periods result in unacceptable changes in product quality. Therefore, novel methods that can shorten the thawing and tempering time and improve the product quality are important for frozen food industry.

Microwave tempering has the advantages of shorter thawing time, and smaller space required for processing and reduction in drip loss. Although microwave tempering has been studied before, there are no studies in literature on infrared assisted microwave tempering. In the food industry, it was paid more attention to the application of ohmic heating on aseptic processing and pasteurization of particulate foods, but using ohmic heating to thaw or temper frozen foods is an innovative method. This study aims to investigate novel methods for tempering. Tylose is used to represent food samples in most of the modeling studies in literature. In this study, frozen potato puree was chosen since it represents a real food system and it is easy to give a shape to it.

The particular element of modeling heat transfer of a food material is the temperature distribution. An accurate model can provide the temperature distribution at any time during the tempering process. Properties of the food material such as density, specific heat, thermal conductivity, and electrical properties are included in the model, and this gives the opportunity to estimate the temperature distribution during the tempering process. The change of the dielectric properties and the heat capacity of the frozen potato puree with respect to temperature and frequency were measured. Numerical modeling was used in this study since it has the advantage of the ease of adaptation when any of the physical properties of foods are changed.

The purpose of this study is to develop a model that can predict the temperature profile inside the frozen potato puree during microwave tempering and infrared assisted microwave tempering processes. Another goal of the study is to compare the tempering of frozen foods by using microwave, infrared assisted microwave, and ohmic heating methods, and to determine if these methods shorten the tempering process significantly.

CHAPTER 2

MATERIALS & METHODS

2.1 Preparation of the Sample

A commercial potato puree powder (Knorr, Turkey) having a moisture content of 6% was used as the sample. The chemical composition of the commercial potato puree powder was 72% carbohydrate, 8% protein, and 1% fat. It contained potato, emulsifier (mono- and diglyceride), stabilizator (disodium diphosphate), food preservative (sodium metabisulphite), spice extract, and antioxidant (ascorbyl palmitate). Boiling water was used to prepare potato puree containing 15% potato puree powder. The potato puree was shaped as a disc with 25 cm diameter and 2.5 cm height for microwave tempering and infrared assisted microwave tempering experiments (Figure 2.1). Sample size was 4.5 cm in diameter and 3 cm in height for ohmic tempering experiments (Figure 2.2). For microwave tempering experiments, the sample was insulated with aluminum foil from the sides and the bottom to provide one-dimensional microwave heating from the top only and was placed in the center of the cavity. Aluminum foil was chosen for insulation since it reflects microwaves. Samples were frozen in a freezer at -30°C and kept for 24 hours. Tiny holes were drilled on the sample before freezing to insert the fiber optic probes during tempering in microwave-infrared combination oven. For ohmic tempering experiments, K-type thermocouples were inserted to the sample and then the sample was frozen.

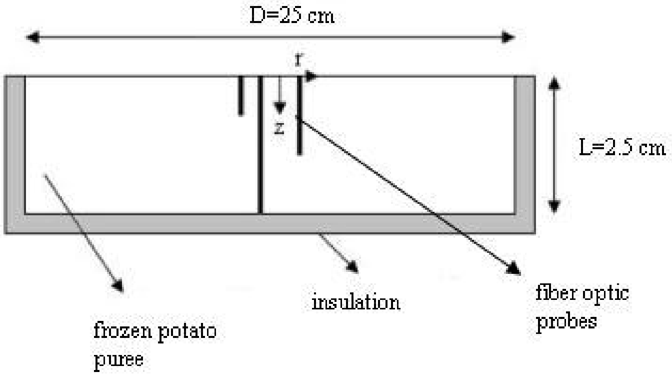

Figure 2.1 View of the frozen potato puree sample for microwave tempering and infrared assisted microwave tempering setup

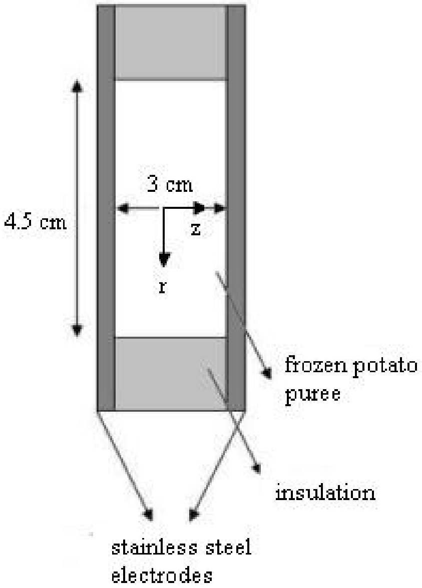

Figure 2.2 View of frozen potato puree sample for ohmic tempering setup

2.2 Microwave Tempering and Infrared Assisted Microwave Tempering

A halogen lamp–microwave combination oven (Advantium oven^{TM}, General Electric Company, Louisville, KY, USA) was used for both microwave tempering and infrared assisted microwave tempering. The power of microwave oven has been determined as 706 W by using IMPI 2-liter test (Buffler, 1993). Three different microwave power levels (30%, 40%, and 50%) were used for microwave tempering. For infrared assisted microwave tempering, lower halogen lamp was not used, and three different upper halogen lamp power levels (10%, 20%, and 30%) were used in combination with the microwave power levels (30%, 40%, and 50%).

2.3 Ohmic Tempering

An ohmic heating unit with stainless steel electrodes was used for ohmic tempering studies (Figure 2.2 & Appendix A). Potato puree samples with three different salt contents (0.5%, 0.75%, and 1.00%) were prepared, frozen, and then tempered by ohmic heating. Three different frequencies (10 kHz, 20 kHz, and 30 kHz) were used for ohmic tempering. Duty cycle, which is defined as the fraction of time the power is on, was 0.7 for all processes.

2.4 Measurement of Temperature

For microwave tempering and infrared assisted microwave tempering experiments, temperatures were measured with fiber optic temperature probes (FOT-L/2M, FISO, Canada) at three different points (0.5 cm, 1.5 cm, and 2.5 cm far from the surface). The temperature data was collected every 10 seconds.

K-type thermocouples were used to collect the temperatures for ohmic tempering. Three thermocouples were inserted to the sample, to the center, to the surface, and in between. Temperatures were recorded in every 10 seconds using a data logger (Agilent 34970A) during the heating process.

2.5 Measurement of Density

The volume of the potato puree (V) with a known weight (m) was measured at -25°C, and the density was calculated by the following density formula:

$$\rho = \frac{m}{V} \tag{12}$$

2.6 Measurement of Heat Capacity

Step scan alternating differential scanning calorimeter (DSC) (Perkin Elmer Diamond DSC, Perkin Elmer, USA) was used to measure the heat capacity of the sample. Hermetically sealed aluminum pans were used to avoid any moisture loss during the test. In the experiment, unfrozen potato puree samples (10–15 mg) were put into the pan, and the pans were sealed. They were cooled to -30°C, held at that temperature for 15 min, and then warmed at heating rate of 10ºC/min from -30ºC to -10ºC. The equation is then extrapolated to -2ºC.

2.7 Measurement of Dielectric Properties

A vector network analyzer (Model: Agilent 8722ES, Agilent Technology, Palo Alto, CA) with an open-ended coaxial cable (#8120-6192, Hewlett Packard) connected to a probe (85070C, Agilent Technology, Palo Alto, CA) was used to measure dielectric properties of potato puree (Appendix B). The built-in S-parameter test set provided a full range of magnitude and phase measurements in both the forward and reverse directions. The instrument was calibrated by measuring the properties of air, short-circuit block, and water at 25°C. To obtain uniform readings, the instrument was turned on at least 2 h before the calibration and measurements were made. The network analyzer probe and the cable were fixed together so that there could be no movement during sample measurement and data acquisition. The dielectric properties of the frozen potato puree were measured in the temperature range of -30ºC to 10ºC for every 2ºC intervals. A thermocouple temperature sensor (BK Precision 390A, Taiwan) was used to monitor the temperature during the study and the temperature variation within the sample was minimal, ±0.5^{o}C. The dielectric properties of the potato puree were measured in the frequency range of 200 to 3000 MHz. The dielectric spectra of the samples (dielectric constant ε', and dielectric loss factor ε'') were automatically computed and recorded with the manufacturer supplied computer software (Version 85070 D1.00, Agilent Technologies, Palo Alto, CA). The measurement was carried out in triplicate.

2.8 Measurement of Electrical Conductivity

The voltage (V) and the current (I) data for every 2°C intervals were read from the ohmic heater (Appendix A) and recorded during ohmic heating experiments, and the resistance of the sample (R) was calculated by using Equation 2. The electrical conductivity (σ) of the food product was calculated using the following equation adapted from Palaniappan & Sastry (1991):

$$\sigma = \left(\frac{1}{R}\right) \times \left(\frac{L}{A}\right) \times 100 \tag{3}$$

where L is the gap between the electrodes (cm), A is the cross-sectional surface area of the electrodes (cm^2), and R is the resistance of the product (ohm).

2.9 Data Analysis

Microsoft Excel software package (Microsoft Corporation, USA) was used to carry out the statistical analysis and the regressions of experimental data. ANOVA (Analysis of Variance) was used to determine if there are significant differences between treatments ($p \leq 0.05$). MATLAB (Version 6.5, The MathWorks Inc.) was used for finite difference modeling.

2.10 Conventional Tempering

The frozen potato puree samples were tempered conventionally by natural convection at 4°C until the sample surface reached to -2°C. The same dimensions were used with the samples used for microwave tempering, infrared assisted microwave tempering, and ohmic tempering.

2.11 Solution of the Mathematical Model

For microwave heating, the energy equation includes a heat generation term. The one-dimensional unsteady state heat conduction equation with heat generation is used to describe microwave heating of material undergoing tempering is:

$$\frac{\partial}{\partial t}(\rho C_p T) = \frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z} \right) + Q_{gen,mw} \tag{13}$$

where ρ (kg/m^3), *Cp* (J/kg.ºC), and *k* (W/m.°C) are the density, heat capacity, and thermal conductivity of the potato puree sample, respectively. $Q_{\mathrm{gen,mw}}$ is the internal heat generation (W/m^3) caused by microwave energy, and assumed as an exponential decay with varying penetration depth (Datta & Ni, 2002), which is commonly related to the microwave surface absorption (Q_0) as follows (Taher & Farid, 2001):

$$Q_{gen,mw} = Q_{0,mw} e^{-(z/Dp,mw)} \tag{14}$$

where D_p is the penetration depth in m. $Q_{0,\ \mathrm{mw}}$ (W/ m^3) was estimated by trial and error to fit the experimental data as Zeng & Faghri (1994) did since a reliable way to measure it directly was not available.

The following initial and boundary conditions are used for microwave tempering:

@ $t = 0$ $\quad 0 < z < L \quad T=T_0$ (15)

@ $t > 0$ $\quad z = 0 \quad -k(T)\frac{\partial T}{\partial z} = h(T - T_\infty)$ (16)

@ $t > 0$ $\quad z = L \quad \frac{\partial T}{\partial z} = 0$ (17)

where L is the thickness of the sample, T_∞ is the surrounding temperature, and h is the convective heat transfer coefficient of between air and the sample. In literature, the heat transfer coefficient values used in a microwave oven ranged from 2 to 39.44 (Chamchong & Datta, 1999a). In this study, it was chosen as 20 W/m^2.°C for microwave tempering, and 30 W/m^2.°C for infrared assisted microwave tempering.

The same one-dimensional unsteady state heat conduction equation is used to describe infrared assisted microwave tempering with a different generation term:

$$\frac{\partial}{\partial t}(\rho C_p T) = \frac{\partial}{\partial z}\left(k(T) \frac{\partial T}{\partial z} \right) + Q_{gen} \tag{18}$$

where Q_{gen} (the total heat generation term) is defined as:

$$Q_{gen} = Q_{gen,mw} + Q_{gen,IR} \tag{19}$$

where $Q_{gen,mw}$ is the internal heat generation (W/m^3) caused by microwave energy, and $Q_{gen,IR}$ is the internal heat generation (W/m^3) caused by infrared energy.

The infrared power flux was also modeled as an exponential decay similar to microwave power (Datta & Ni, 2002) which is expressed by:

$$Q_{gen,IR} = Q_{0,IR} e^{-(z/Dp,IR)} \tag{20}$$

where $Q_{0,IR}$ is infrared surface flux, and $D_{p,IR}$ is infrared penetration depth which is defined exactly as microwave penetration depth. For this study, $D_{p,IR}$ is taken as 3.5 mm which was the $D_{p,IR}$ value for potato tissues from the study of Almeida *et al.* (2006). $Q_{0,IR}$ was estimated by trial and error to fit the experimental data.

In infrared assisted microwave heating, on-off cycling of infrared heating depending on the halogen lamp power is important. Such cycling is generally done by turning infrared source on for some of the time during the cycle and turning it off during the rest of the cycle. The fraction of time the power is on is called as Duty cycle and defined as (Chamchong & Datta, 1999a):

$$Duty\ cycle = \frac{t_{on}}{t_{on} + t_{off}} \tag{21}$$

The time values t_{on} and t_{off} changes with changing halogen lamp power. When the halogen lamp power is increased, t_{on} also increases and t_{off} decreases.

To solve near-infrared assisted microwave tempering equations, the same boundary conditions are used with microwave tempering.

To predict the temperature profile inside the frozen potato puree sample, the mathematical model was solved numerically by using the initial and boundary conditions. Explicit finite difference method was used to solve the governing equations. Heat capacity, thermal conductivity, and the penetration depth were taken as dependent on temperature.

One-dimensional unsteady state heat conduction equation can be written as;

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C_p(T)} \cdot \left[\frac{\partial}{\partial z}\left(k(T) \frac{\partial T}{\partial z} \right) + Q_{gen} \right] \tag{22}$$

If w is defined as;

$$w = \frac{1}{\rho C_p(T)} \tag{23}$$

The Equation 22 becomes:

$$\frac{\partial T}{\partial t} = w(T) \cdot \left[\frac{\partial}{\partial z}\left(k(T) \frac{\partial T}{\partial z} \right) + Q_{gen} \right] \tag{24}$$

$$\frac{\partial T}{\partial t} = w(T) \cdot \left[\frac{\partial k}{\partial z} \frac{\partial T}{\partial z} + k(T) \frac{\partial^2 T}{\partial z^2} + Q_{gen} \right] \tag{25}$$

$$\frac{\partial k}{\partial z} = \frac{\partial k}{\partial T} \frac{\partial T}{\partial z} \tag{26}$$

By substituting Equation 26 into Equation 25;

$$\frac{\partial T}{\partial t} = w(T) \cdot \left[\left(\frac{\partial k}{\partial T} \cdot \left(\frac{\partial T}{\partial z} \right)^2 + k(T) \cdot \frac{\partial^2 T}{\partial z^2} \right) + Q_{gen} \right] \tag{27}$$

Finite difference expressions are given as follows:

$$\frac{\partial T}{\partial t} = \frac{T_i^{n+1} - T_i^n}{\Delta t} \tag{28}$$

$$\frac{\partial T}{\partial z} = \frac{T_{i+1}^n - T_{i-1}^n}{2\Delta z} \tag{29}$$

$$\frac{\partial^2 T}{\partial z^2} = \frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{(\Delta z)^2} \tag{30}$$

$$\frac{T_i^{n+1} - T_i^n}{\Delta t} = w(T) \cdot \left[\left(\frac{\partial k}{\partial T} \cdot \left(\frac{T_{i+1}^n - T_{i-1}^n}{2\Delta z} \right)^2 + k(T) \cdot \left(\frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{(\Delta z)^2} \right) \right) + Q_{gen} \right] \tag{31}$$

Initially, the temperature is uniform inside the sample. That is;

I.C. $@\, t = 0 \quad T = T_0$ for $0 \le z \le L$ (32)

The first boundary condition is:

$$@\ z = 0 \qquad -k(T)\frac{\partial T}{\partial z} = -h(T - T_\infty) \tag{33}$$

$$k_i.\frac{T_{i+1} - T_{i-1}}{2\Delta z} = h.(T_i - T_\infty) \tag{34}$$

$$T_{i+1} - T_{i-1} = \frac{2h\Delta z}{k_i}\cdot(T_i - T_\infty) \tag{35}$$

$$T_{i-1} = T_{i+1} + \frac{2h\Delta z}{k_i}\cdot(T_\infty - T_i) \tag{36}$$

$$T_i^{n+1} = T_i^n + \Delta t.w_i \cdot \left[\left(\frac{\partial k}{\partial T}\cdot\left(\frac{T_{i+1}^n - T_{i-1}^n}{2\Delta z}\right)^2 + k_i\cdot\left(\frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{(\Delta z)^2}\right)\right) + Q_i\right] \tag{37}$$

The second boundary condition is:

$$@\ z = L \qquad \frac{\partial T}{\partial z} = 0 \tag{38}$$

$$\frac{T_{i+1} - T_{i-1}}{2\Delta z} = 0 \tag{39}$$

$$T_{i+1} = T_{i-1} \tag{40}$$

$$T_i^{n+1} = T_i^n + \Delta t.w_i \cdot \left[\left(\frac{\partial k}{\partial T}\cdot\left(\frac{T_{i+1}^n - T_{i-1}^n}{2\Delta z}\right)^2 + k_i\cdot\left(\frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{(\Delta z)^2}\right)\right) + Q_i\right] \tag{41}$$

For the other nodes, the finite difference expression is:

$$T_i^{n+1} = T_i^n + \Delta t . w_i \cdot \left[\left(\frac{\partial k}{\partial T} \cdot \left(\frac{T_{i+1}^n - T_{i-1}^n}{2\Delta z} \right)^2 + k_i \cdot \left(\frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{(\Delta z)^2} \right) \right) + Q_i \right] \quad (42)$$

where i denotes the node position, n is the time interval, and Δz and Δt are the spatial and time increments, respectively. Δz was chosen as 0.001 and Δt was chosen as 0.0005 for this study, and the method was stable with these increment values.

CHAPTER 3

RESULTS & DISCUSSION

3.1 Physical Properties of Frozen Potato Puree

The density, heat capacity and the dielectric properties of frozen potato puree sample were measured. These properties were necessary for modeling purposes.

3.1.1 Density of Frozen Potato Puree

The density of the potato puree sample was measured as 1395 kg/m^3 by using Equation 12.

3.1.2 Heat Capacity of Frozen Potato Puree

The specific heat capacity is the amount of heat required to change a unit mass of a substance by one degree in temperature. Heat capacity of food is important for heat transfer since it determines how fast a food can be heated. The variation of heat capacity of the frozen potato puree sample with temperature is shown in Appendix C. The heat capacity of potato puree was observed to increase with increasing temperature. Predictive equation for the heat capacity obtained from this result (r^2=0.99) and used for the modeling is given as follows:

$$C_p(T) = 2087.8 + 21.058 \times T + 0.2224 \times T^2 \tag{43}$$

3.1.3 Dielectric Properties of Frozen Potato Puree

Figures 3.1 and 3.2 show the change of dielectric constant (ε′) and loss factor (ε″) of the frozen potato puree with respect to temperature, respectively. Results indicated that the dielectric constant and loss factor of potato puree samples increased exponentially as the temperature increased. Both dielectric parameters were found to be very low (3 to 10 for dielectric constant and 0 to 3 for loss factor) up to -10°C and level off at above -2°C. During thawing, both dielectric constant and loss factor show large increases with temperature. After thawing, dielectric properties of foods are known to decrease with increasing temperature (Sahin & Sumnu, 2006). Free and bound moisture content affect the rate of change of dielectric constant and loss factor with temperature. If the water is in bound form, the increase in temperature increases the dielectric properties. However, in the presence of free water, dielectric properties of free water decrease as temperature increases. At high temperatures, hydrogen bonds become rare. Less energy is required to overcome intermolecular bond at higher temperatures that results in lower dielectric properties. Therefore, the rate of variation of dielectric properties depends on the ratio of bound to free moisture content (Sahin & Sumnu, 2006). The values of both dielectric constant and loss factor at 2450 MHz and -17.7°C were found to be rather small for frozen mashed potatoes by Regier *et al*. (2001). Ice is known to have lower dielectric constant and loss factor as compared to that of water (Schiffman, 1986). The dielectric constant and loss factor of ice is 3.2 and 0.0029, respectively, and the dielectric constant and loss factor of water is 78 and 12.48, respectively at 2450 MHz.

The dielectric constant decreased slightly whereas loss factor increased significantly as the frequency was increased (Figures 3.1 and 3.2). The same trend was observed for frozen tylose samples in literature (Chamchong, 1997).

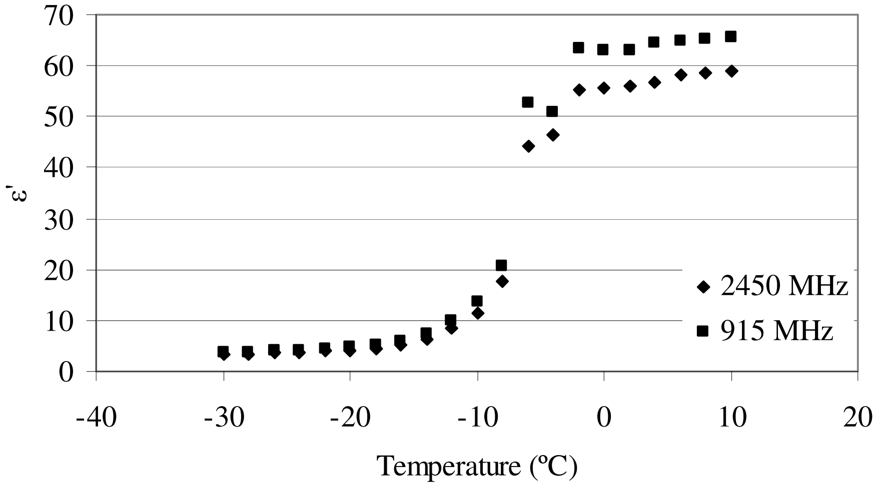

Figure 3.1 Effect of temperature on dielectric constant of frozen potato puree

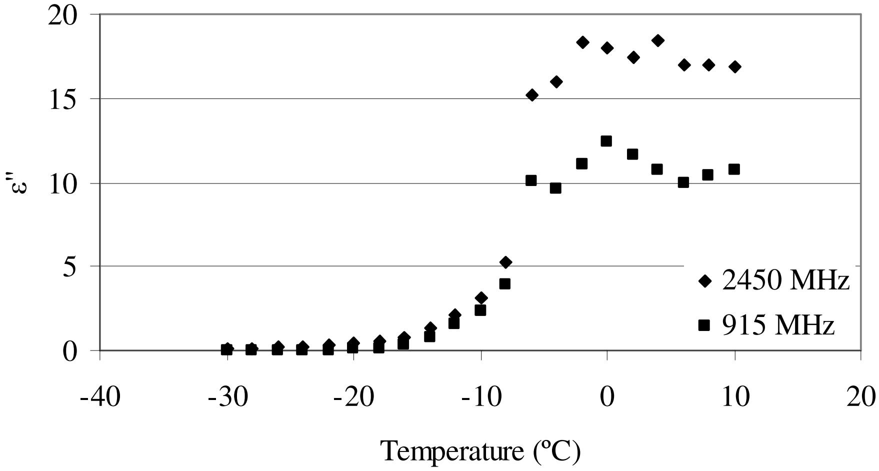

Figure 3.2 Effect of temperature on loss factor of frozen potato puree

Predictive equations were fitted to the results and given in Table 3.1. In literature, dielectric constant was reported to be predicted better than the loss factor (Guan *et al.*, 2004). These results are important for microwave thawing and tempering of frozen potato puree studies and can be used for modeling purposes to estimate the thawing or tempering time and temperature distribution during microwave heating. The dielectric properties at 2450 MHz were used for modeling in this study.

Table 3.1 Predictive equations for dielectric constant (ε′) and loss factor (ε″) of frozen potato puree

	Frequency	Temperature range	Equation	r^2
ε′	915 MHz	-30ºC < T≤ -2ºC	$y = 0.1541x^2 + 6.8022x + 74.837$	0.92
		-2ºC < T ≤ 0ºC	$y = 0.0086x^2 + 0.1691x + 63.197$	0.90
	2450 MHz	-30ºC < T ≤ -2ºC	$y = 0.1377x^2 + 6.0395x + 65.88$	0.92
		-2ºC < T ≤ 10ºC	$y = 0.0116x^2 + 0.2573x + 55.645$	0.96
ε″	915 MHz	-30ºC < T ≤ -8ºC	$y = 0.0152x^2 + 0.7182x + 8.199$	0.95
		-8ºC < T ≤ 10ºC	$y = -0.049x^2 + 0.2921 + 11.415$	0.68
	2450 MHz	-30ºC < T ≤ -8ºC	$y = 0.0178x^2 + 0.8565x + 10.21$	0.94
		-8ºC < T ≤ 10ºC	$y = -0.0838x^2 + 0.5358x + 18.251$	0.76

The penetration depths are calculated by using Equation 1. As microwaves move through the slab at any point, the rate of heat generated per unit volume decreases. For materials having high loss factor, the rate of heat generated decreases rapidly and microwave energy does not penetrate deeply. A parameter called penetration depth indicates the distance that microwaves will penetrate into the material before it is reduced to 1/e of its initial value (Sahin & Sumnu, 2006). The penetration depth (D_p) of the frozen samples at selected microwave frequencies (915 and 2450 MHz) decreased as a function of temperature (Figure 3.3). The decrease was more significant at lower temperatures and the penetration depth became almost constant after -6°C. The penetration depth at 915 MHz was significantly higher than the penetration depth at 2450 MHz at lower temperatures. This is one of the reasons why 915 MHz is recommended in industrial heating.

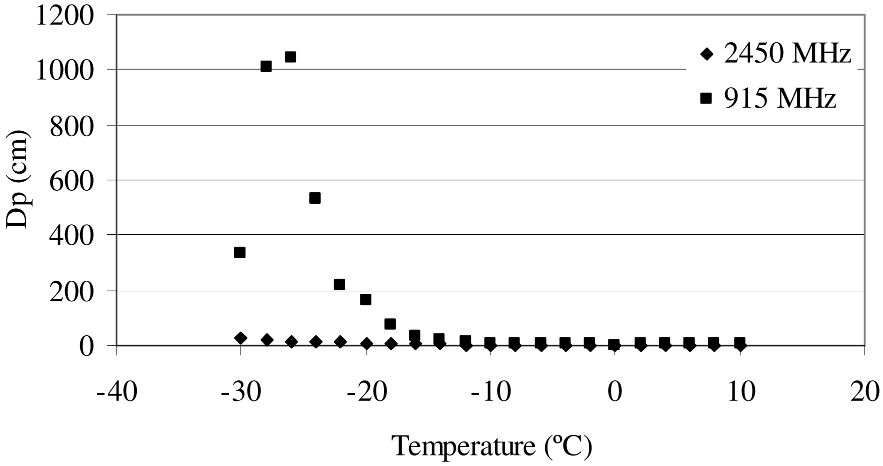

Figure 3.3 Effect of temperature on penetration depths of frozen potato puree

Figures 3.4 and 3.5 show the effect of frequency on dielectric constant (ε′) and loss factor (ε″) of the frozen potato puree, respectively. At low temperatures (less than -12°C), both dielectric properties seemed to be very low and almost constant, whereas both dielectric constant and loss factor values increased as the temperature increased to -6°C and higher. Temperature dependence of dielectric properties is explained by relaxation phenomena that occur at that temperature and frequency range. It is stated that the dielectric constant should increase with the temperature in the region of dispersion since the relaxation time of the polar molecules decreases with increasing temperature (Motwani *et al.*, 2007). At low temperatures, both dielectric properties seemed to be independent from frequency, but effect of frequency could be observed at higher temperatures. The dielectric constant of sample exhibited a decrease with increasing frequency at higher temperatures. The dielectric constant of water also decreases with increasing frequency at positive temperatures (0°C - 60°C) (Venkatesh & Raghavan, 2004). Microwave heating is greatly affected by the presence of water in foods, so the decrease in dielectric constant is in accordance with that of water. The loss factor showed a decrease in the frequency range of 200 - 480 MHz and an increase in the higher frequency range of 480 - 3000 MHz (Figure 3.5). With increase in frequency, the polar molecules are unable to keep up with change in the orientation of the imposed electromagnetic field, thus causing a lag. This results in dissipation of energy, which is indicated by a decrease in dielectric constant and an increase in the dielectric loss factor. The same U-shape behavior for loss factor was observed at corn starch slurries and pure water in the same frequency range (Motwani *et al.*, 2007). The loss factor also increased with increasing temperature up to 0°C but then exhibited a decrease after 0°C.

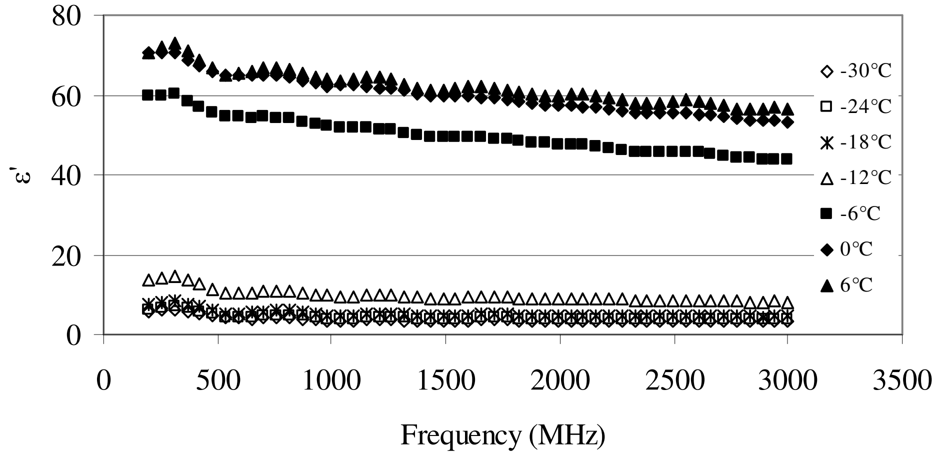

Figure 3.4 Effect of frequency on dielectric constant of frozen potato puree at different temperatures

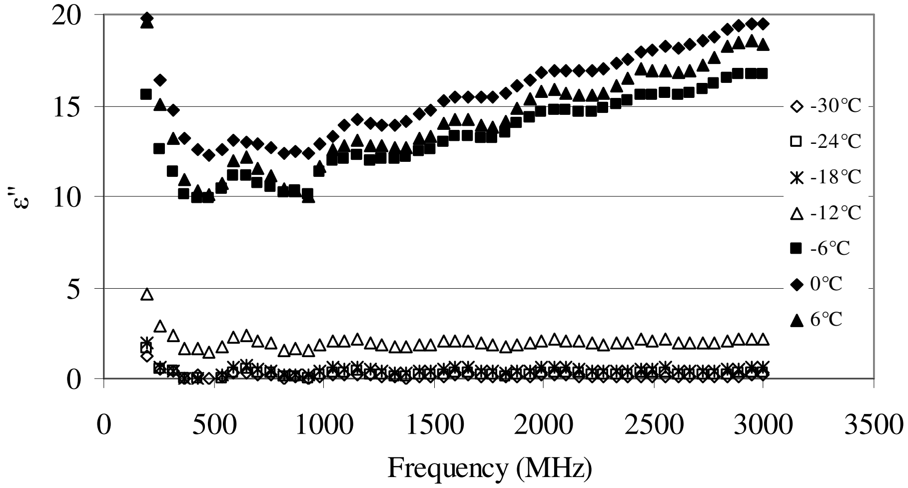

Figure 3.5 Effect of frequency on loss factor of frozen potato puree at different temperatures

3.2 Modeling of Microwave Tempering

In this study, tempering time is defined as the time needed for the surface temperature of frozen potato puree sample to reach -2°C. The microwave tempering times of frozen potato puree are given in Table 3.2. When the microwave power was increased, the tempering time got shorter as expected.

Table 3.2 Tempering times for microwave heating

Microwave power	30%	40%	50%
Tempering time (s)	630	440	330

The temperature profiles during tempering with different microwave powers are given in Figures 3.6, 3.7, and 3.8. Different markers indicate different thermocouple positions inside the frozen potato puree sample. It can be seen from the figures that temperature distribution is more uniform at lower microwave powers since tempering time is longer at lower microwave powers allowing also conduction to take place.

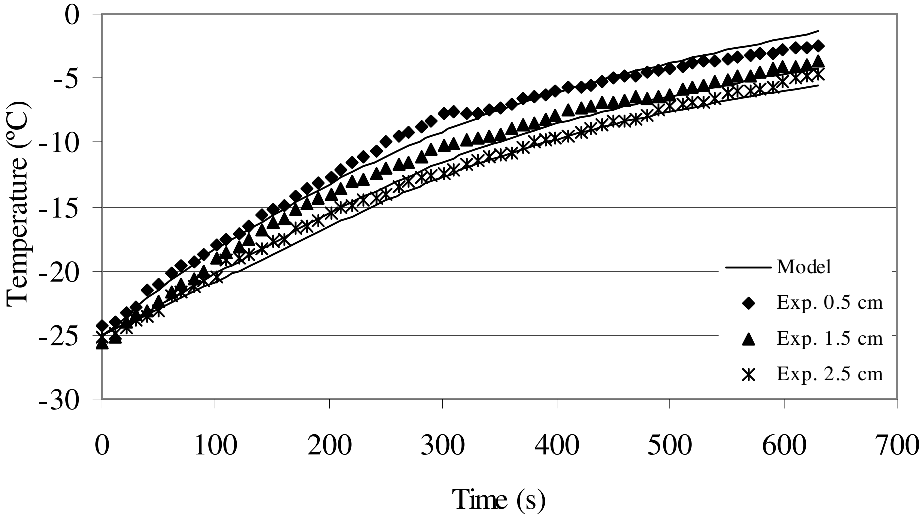

Figure 3.6 Temperature distribution in frozen potato puree during tempering at 30% microwave power

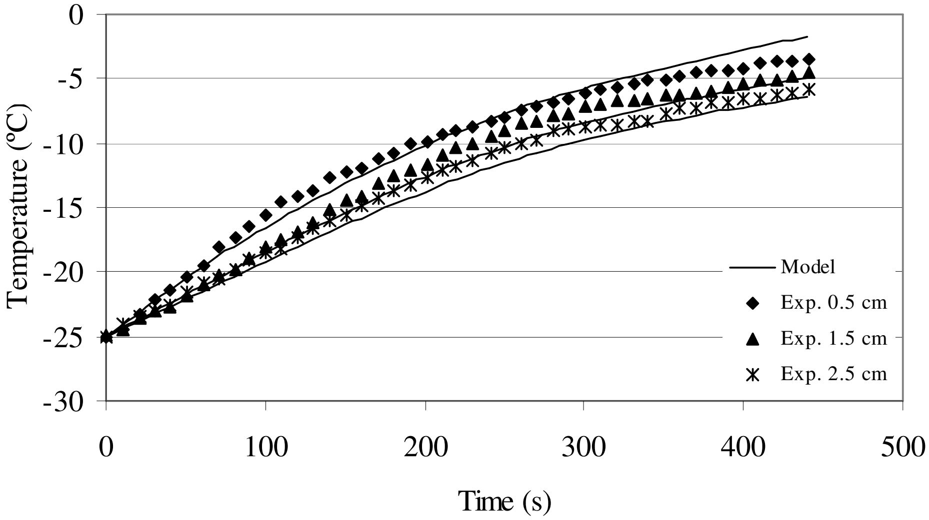

Figure 3.7 Temperature distribution in frozen potato puree during tempering at 40% microwave power

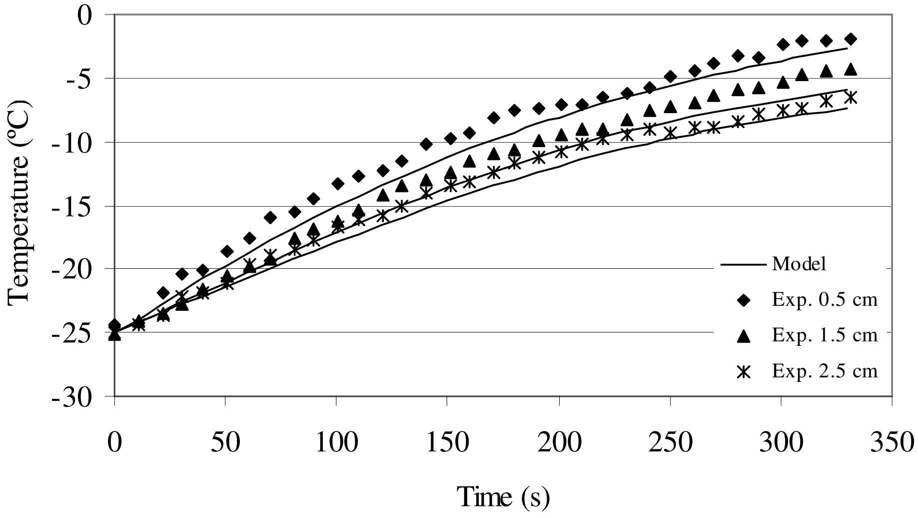

Figure 3.8 Temperature distribution in frozen potato puree during tempering at 50% microwave power

Moisture loss of frozen potato puree was determined during microwave tempering, and it was found that moisture loss was not significant (less than 1%). Therefore, moisture loss was assumed to have negligible effect on the heat transfer during tempering and also on the physical properties of the frozen potato puree. Chamchong & Datta (1999a) also found that average moisture loss during microwave thawing was less than or equal to 1% and could be assumed to be negligible during thawing. Thus, the physical properties of potato puree were taken as only temperature dependent.

Finite difference method was used to model the temperature distribution during microwave tempering. To simplify the governing equations and boundary conditions, several assumptions have been done. First of all, the initial temperature was considered as uniform within the sample. The sides and the bottom of the sample were insulated by aluminum foil, so the heat transfer was assumed to be one dimensional. Aluminum foil is not heated in microwave oven since it reflects microwaves. Thus, the resulting one-dimensional unsteady state heat conduction equation with heat generation (Equation 18) was used to describe microwave heating of material undergoing tempering.

The empirical equation for Cp values given in Equation 43 was used in modeling. The thermal conductivity of frozen potato puree was estimated by Equation 44 (Choi & Okos, 1986):

$$k(T) = 2.01 + 1.39\times10^{-3} \times T - 4.33\times10^{-6} \times T^{2} \qquad (44)$$

where T is temperature in °C, and k is thermal conductivity (W/m.°C).

$Q_{\mathrm{gen,mw}}$ was assumed as an exponential decay with varying penetration depth (Datta & Ni, 2002), which is commonly related to the microwave surface absorption ($Q_{0,mw}$) as follows (Taher & Farid, 2001):

$$Q_{gen,mw} = Q_{0,mw} e^{-(z/Dp,mw)} \qquad (14)$$

where D_p is the penetration depth in m. $Q_{0,\mathrm{mw}}$ (W/m^3) was estimated by trial and error to fit the experimental data as Zeng & Faghri (1994) did since a reliable way to measure it directly was not available. For D_p calculation, Equation 1 was used. The predictive equations for dielectric constant and loss factor given in Table 3.1 were used to calculate the penetration depth at 2450 MHz.

The MATLAB program used for modeling microwave tempering is given in Appendix D, and the input parameters used in modeling are summarized in Appendix E. In literature, the heat transfer coefficient values used in a microwave oven ranged from 2 to 39.44 (Chamchong & Datta, 1999a). In this study, it was chosen as 20 W/m^2.°C for microwave tempering.

Figures 3.6 - 3.8 shows both computed and experimental temperature values at different thermocouple positions for microwave tempering at different microwave power levels. Experimental data are shown by markers and lines represent the model predicted. The predicted temperatures show good agreement with the experimental results. The r^2 values ranged between 0.990 - 0.998. The bottom of the sample was heated slower since microwave power flux decreased within the sample as an exponential decay.

3.3 Modeling of Infrared Assisted Microwave Tempering

Times necessary to temper frozen potato puree in infrared assisted microwave oven are given in Table 3.3. As can be seen from the table, using infrared heating in combination with microwaves decreased the tempering time. In addition, increasing infrared power level resulted in lower tempering times.

Table 3.3 Tempering times for infrared assisted microwave tempering

Microwave power	**30%**			**40%**			**50%**		
Infrared power	10%	20%	30%	10%	20%	30%	10%	20%	30%
Tempering time (s)	320	240	200	250	210	170	210	170	150

Finite difference method was used to model the temperature distribution during infrared assisted microwave tempering (Appendix F). In this part of the study, the heat transfer coefficient was chosen as 30 W/m^2.°C for infrared assisted microwave tempering because of the addition of infrared heating. In the oven, there are two infrared heating sources: halogen lamp at the top and halogen lamp at the bottom. The lamp at the bottom of the oven was not used to achieve one-dimensional heat transfer during infrared assisted microwave tempering. The same one-dimensional unsteady state heat conduction equation used for microwave tempering is used to describe near-infrared assisted microwave tempering with a different generation term (Equation 19). For this study, $D_{p,inf}$ is taken as 3.5 mm for potato tissues from Almeida *et al.* (2006). $Q_{0,inf}$ was estimated by trial and error to fit the experimental data.

The temperature profiles during tempering with infrared assisted microwave heating with different infrared powers and microwave powers are given in Figures 3.9 – 3.17. Different markers indicate different thermocouple positions inside the frozen potato puree sample. As can be observed from these figures, the heating pattern seems to be different from microwave tempering (Figures 3.6 – 3.8). The stepwise changes seen in temperature profile are due to on-off cycling of infrared heating depending on the infrared power. Actually, microwave heating also has on-off cycling, but due to very low dielectric properties of frozen sample the effect of microwave cycling cannot be observed on temperature profile of frozen potato puree during microwave tempering.

It was observed that at the same microwave power level, increasing the infrared power increases the height of the steps in stepwise changes on the temperature profile, resulting in a more non-uniform temperature distribution since when the infrared power increased, the halogen lamp (the source of infrared heating) is on for a longer time, i.e. the sample is exposed to infrared heating more (Figures 3.11, 3.14, 3.17). Also, at the same infrared power level, increasing the microwave power level increased the non-uniformity in the temperature distribution during tempering (Figures 3.9, 3.12, 3.15). At 30% microwave plus 10% infrared level, the temperature profile is the most uniform one. The effect of infrared heating is observed as more dominant at the lowest microwave power level (Figures 3.9 and 3.15), but infrared heating adds non-uniformity to the temperature distribution.

Considering the experimental data and the model, the match between the two is very good. The r^2 values ranged between 0.985-0.998. It is worth to note that how the model well predicted the onset and the offset of the heating profile.

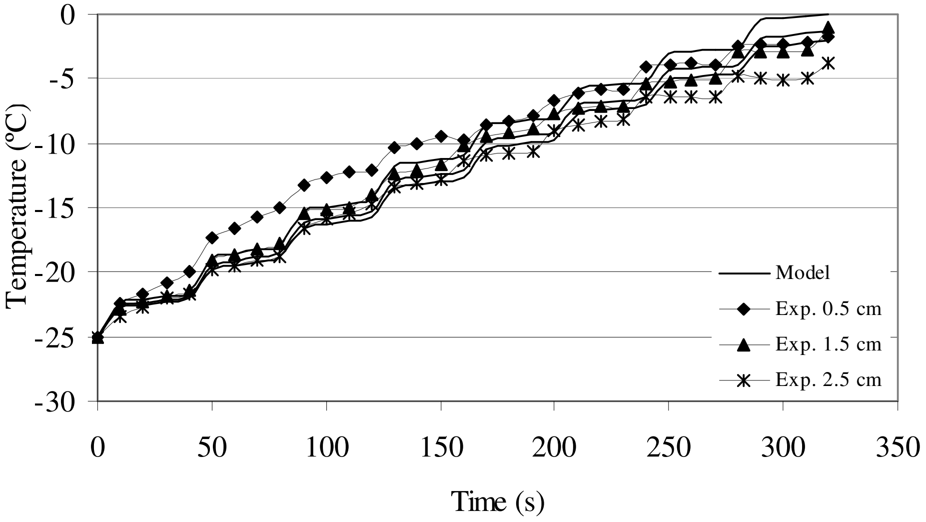

Figure 3.9 Temperature profile of frozen potato puree during tempering at 30% microwave power and 10% infrared power

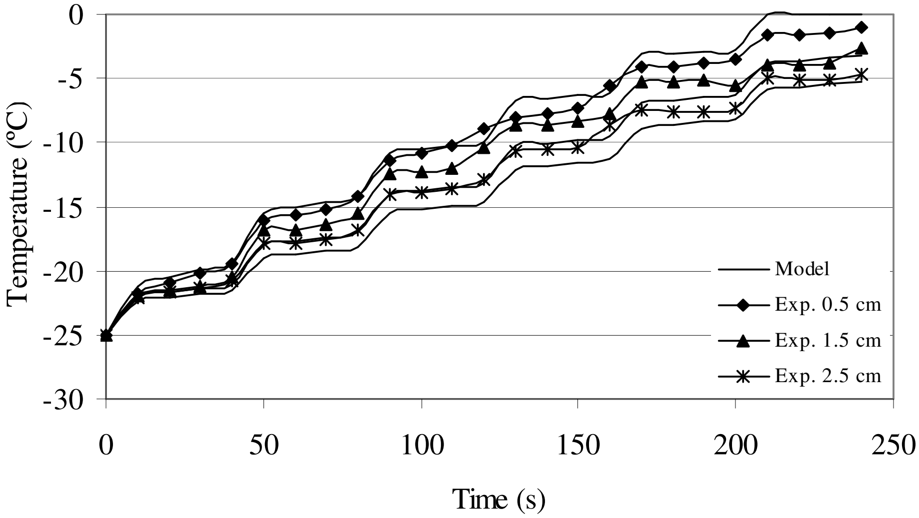

Figure 3.10 Temperature profile of frozen potato puree during tempering at 30% microwave power and 20% infrared power

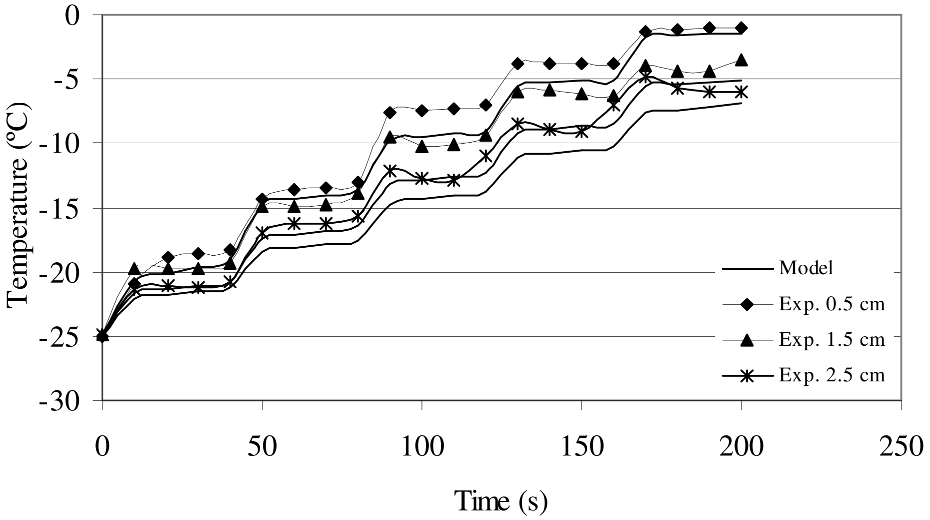

Figure 3.11 Temperature profile of frozen potato puree during tempering at 30% microwave power and 30% infrared power

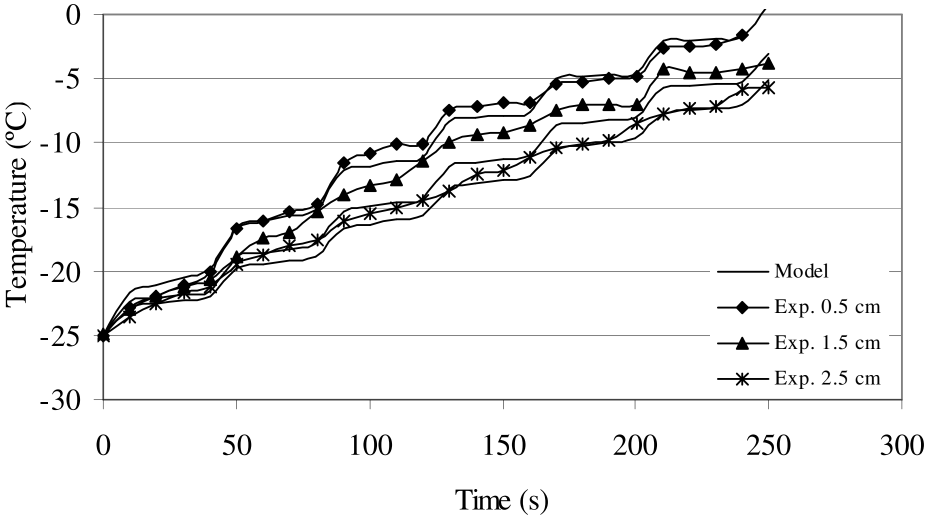

Figure 3.12 Temperature profile of frozen potato puree during tempering at 40% microwave power and 10% infrared power

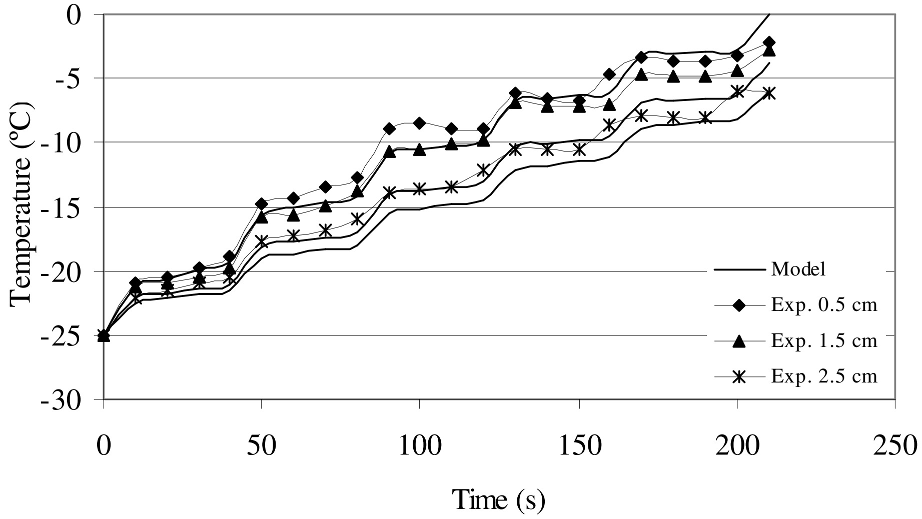

Figure 3.13 Temperature profile of frozen potato puree during tempering at 40% microwave power and 20% infrared power

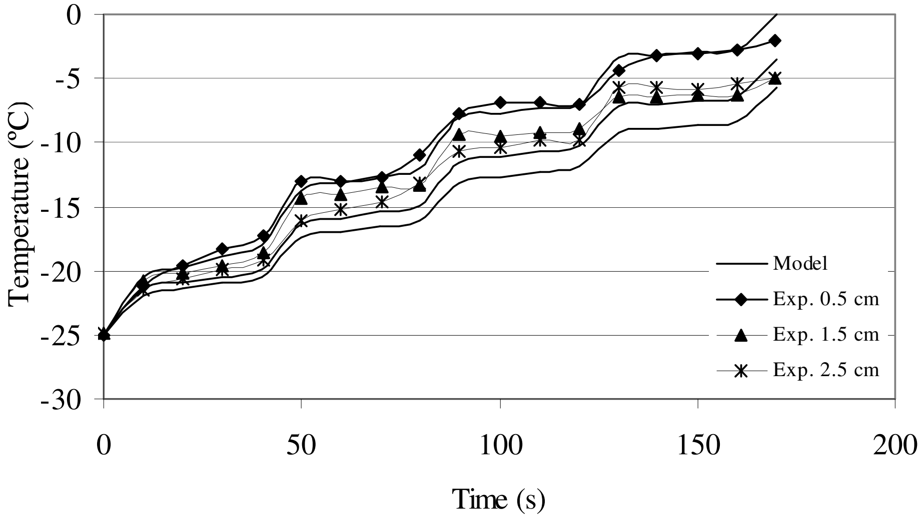

Figure 3.14 Temperature profile of frozen potato puree during tempering at 40% microwave power and 30% infrared power

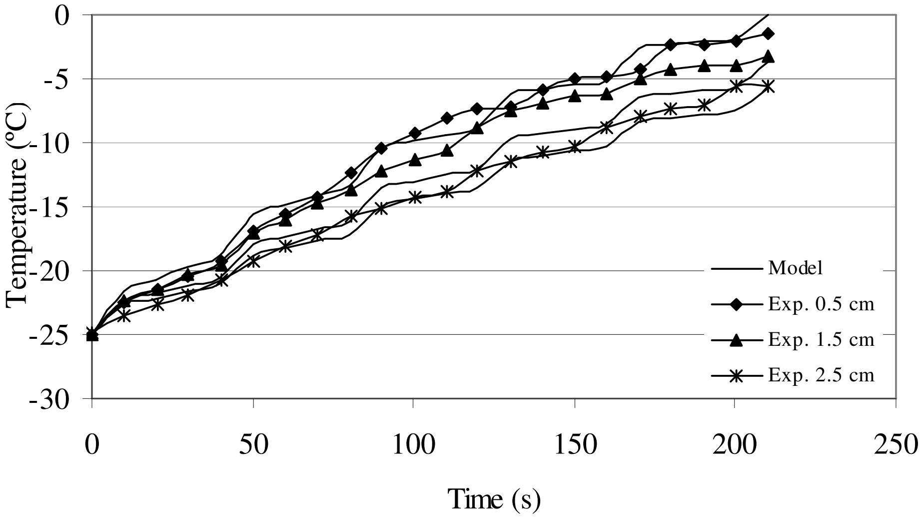

Figure 3.15 Temperature profile of frozen potato puree during tempering at 50% microwave power and 10% infrared power

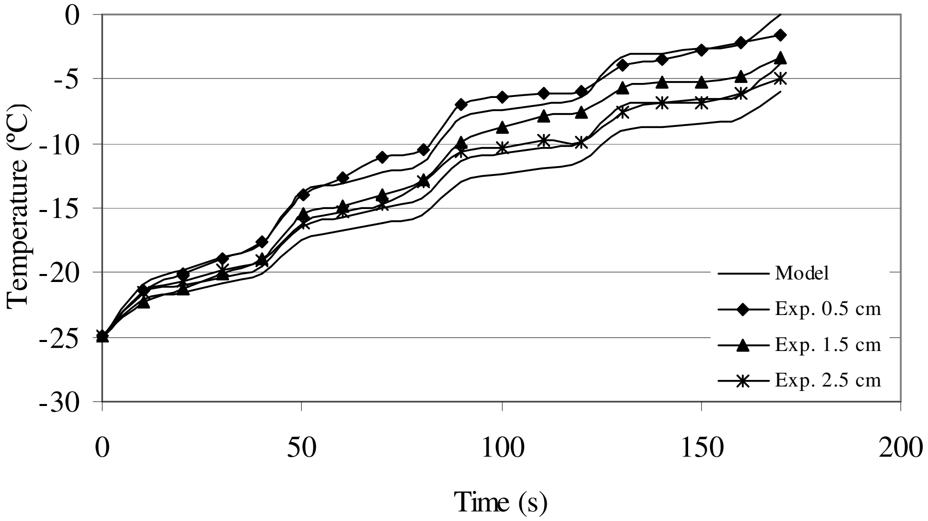

Figure 3.16 Temperature profile of frozen potato puree during tempering at 50% microwave power and 20% infrared power

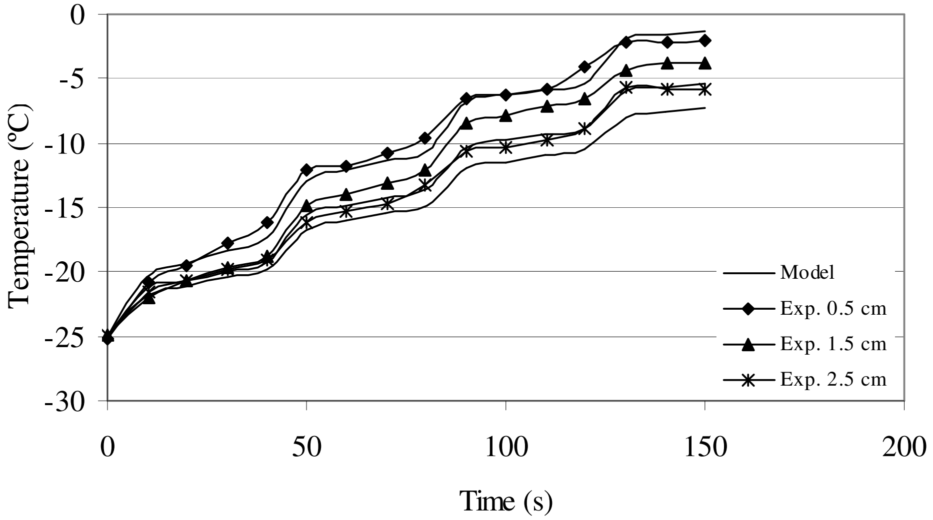

Figure 3.17 Temperature profile of frozen potato puree during tempering at 50% microwave power and 30% infrared power

Figures 3.18-3.20 show the effect of different infrared power levels combined with three different microwave powers on temperature profile of frozen potato puree at the position of 1.5 cm below the surface. Infrared heating provided an additional flux and shortened tempering time significantly as illustrated in Figures 3.18 - 3.20.

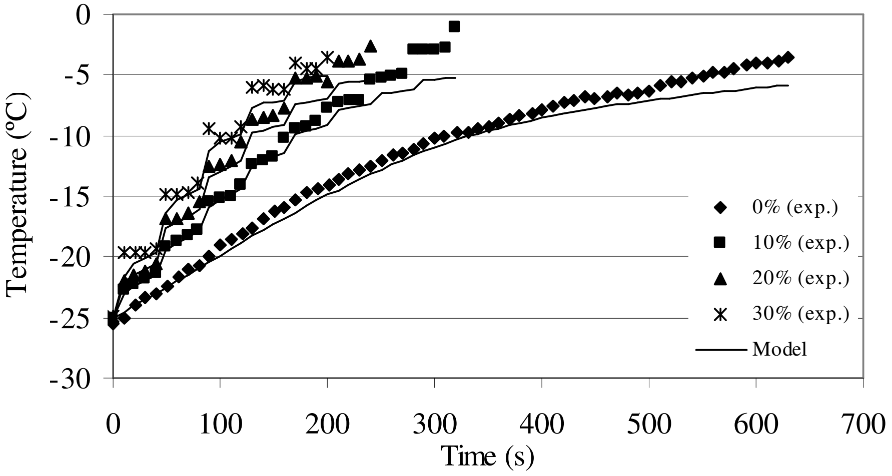

Figure 3.18 Effect of infrared power on variation of temperature at 1.5 cm depth during tempering of frozen potato puree at 30% microwave power

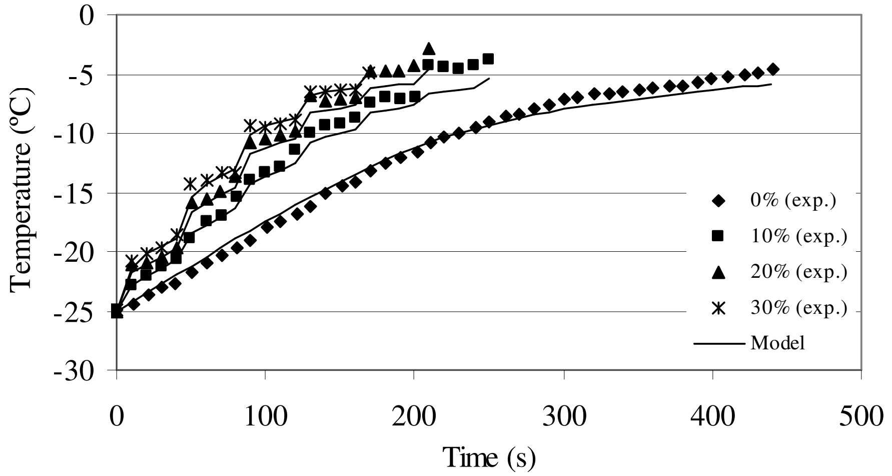

Figure 3.19 Effect of infrared power on variation of temperature at 1.5 cm depth during tempering of frozen potato puree at 40% microwave power

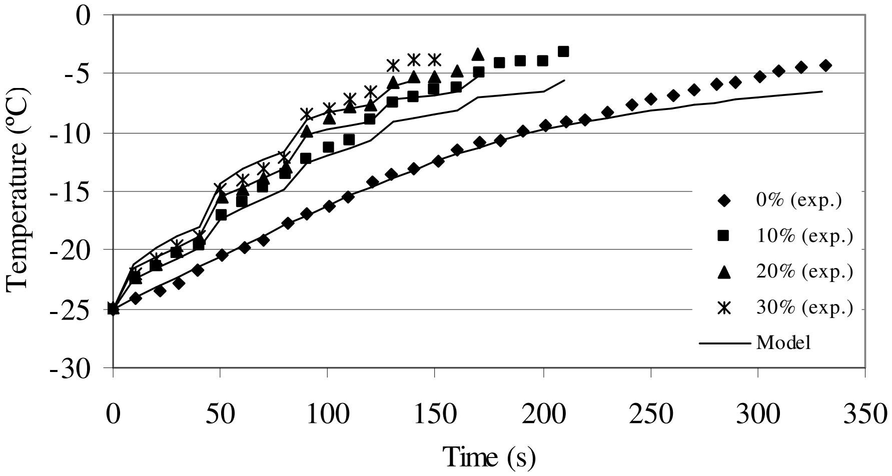

Figure 3.20 Effect of infrared power on variation of temperature at 1.5 cm depth during tempering of frozen potato puree at 50% microwave power

3.5 Ohmic Tempering

Different frequencies were used for ohmic tempering studies to observe the effect of the frequency on tempering time and temperature distribution. As discussed before, electrical conductivity is a very important parameter for ohmic heating studies. It is strongly dependent on salt content, so different levels of salt were used to improve the electrical conductivity. The maximum level of salt used was 1.00% since more salty foods may not be acceptable in food industry.

At the beginning of the study, it was thought to use the same experimental conditions (same sample size and initial temperature) with microwave tempering and infrared assisted microwave tempering studies for ohmic tempering. But due to the limitations of the size of the electrodes of ohmic heating unit, the same size could not be used and a different diameter for the frozen potato puree sample had to be selected. In the preliminary experiments, different thicknesses (5 to 20 cm) were tried, but when thick samples were used no current was observed. It was concluded that the distance between the electrodes is an important parameter in designing ohmic heating units.

The samples were frozen to -25°C, but no current was observed at that temperature level, meaning that ohmic heating was not effective. To understand the reason of this problem, a set of experiments were performed with water including very high levels of salt like 10%, 20%, 30%, and these salt solutions were chilled. Since addition of salt decreased the freezing point of the salt solutions, the solutions that were not frozen but chilled (still in liquid state) were heated so fast by ohmic heating. However, the solutions that were frozen (in solid state) could not be tempered by ohmic heating. Thus, it was concluded that the physical state of the food sample was also very important for ohmic heating studies, since it was harder to conduct electricity in solid bodies. The lowest possible temperature level to observe current for all different ohmic tempering conditions was -15°C, so the initial temperature for ohmic tempering experiments was selected as -15°C.

Electrical conductivities of frozen potato purees during tempering process were calculated by using Equation 3. The effects of salt content and frequency on the electrical conductivity of frozen potato puree are given in Figures 3.21 and 3.22, respectively. It is clearly observed from both figures that as the temperature increased, the electrical conductivity of frozen potato puree also increased. This behavior was expected since the electrical conductivity increases substantially with temperature (Palaniappan & Sastry, 1991). Electrical current flow increases with increasing temperature, and according to Ohm's Law (Equation 2) the resistance of the sample decreases, meaning an increase in electrical conductivity. Figure 3.21 shows the effect of salt content on the electrical conductivity values during tempering. As the salt concentration increased, the electrical conductivity increased. The effect is more pronounced at relatively higher temperatures. According to ANOVA results, the salt content significantly affected the electrical conductivity values of frozen potato puree (Appendix G). Increasing frequency also increased the electrical conductivity values of frozen potato puree (Figure 3.22).

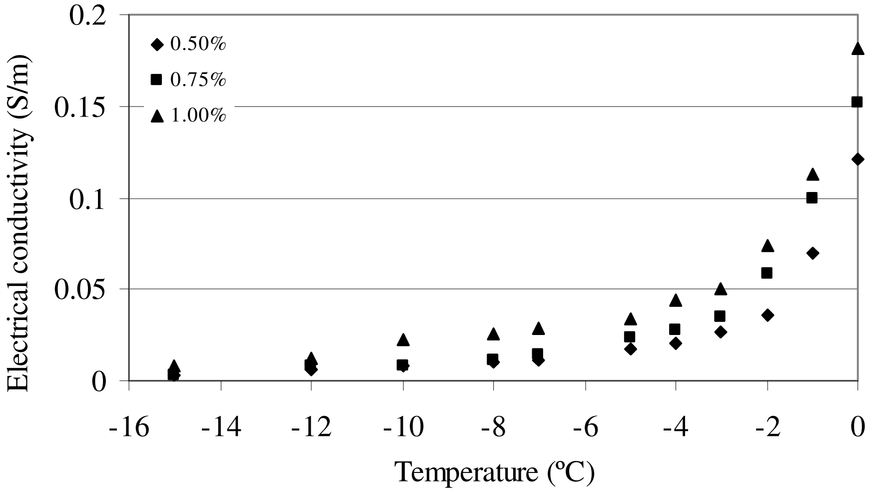

Figure 3.21 Effect of salt content on electrical conductivity of frozen potato puree

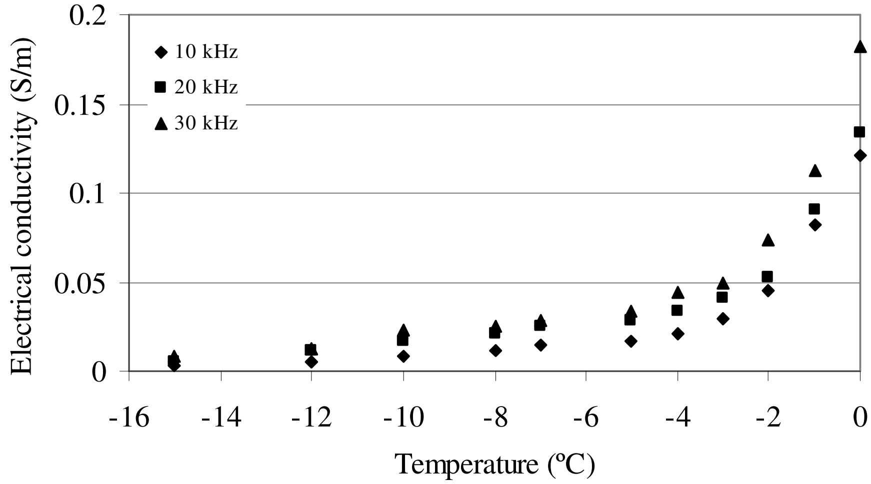

Figure 3.22 Effect of frequency on electrical conductivity of frozen potato puree

Tempering times for different ohmic tempering conditions are summarized in Table 3.4. As can be seen from the table, increase in salt content and frequency decreased the tempering times. Addition of salt increased the electrical conductivity of the sample, resulting in lower tempering times. Increasing frequency also increased the electrical conductivity and shortened the tempering times.

Table 3.4 Tempering times for ohmic heating

Salt content	**1.00%**			**0.75%**			**0.50%**		
Frequency	10 kHz	20 kHz	30 kHz	10 kHz	20 kHz	30 kHz	10 kHz	20 kHz	30 kHz
Tempering time (s)	250	240	210	300	290	260	430	400	330

The temperature profiles during different ohmic tempering conditions are given in Figures 3.23 – 3.31. Different markers indicate different thermocouple positions inside the frozen potato puree sample. At 10 kHz, the temperature distribution is more homogeneous inside the frozen potato puree sample, since the tempering time is longer and this allows longer conduction resulting in a more homogenous temperature distribution (Figures 3.23 - 3.25). According to ANOVA there was no significant difference between the thermocouple positions for ohmic tempering for 10 kHz, meaning that the temperature distribution was uniform (Appendix G). On the other hand, temperatures at different thermocouple positions were significantly different for ohmic tempering at 20 kHz and 30 kHz (Figures 3.26 - 3.31).

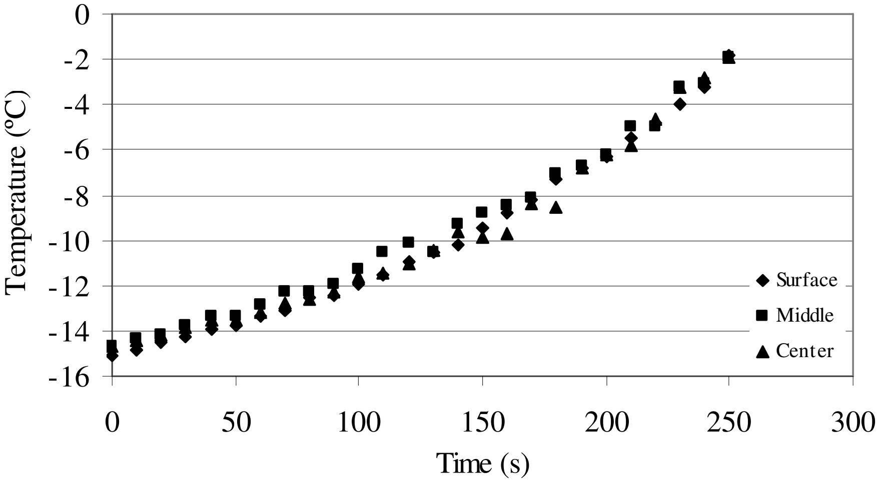

Figure 3.23 Temperature profile of frozen potato puree with 1.00% salt during ohmic tempering at 10 kHz

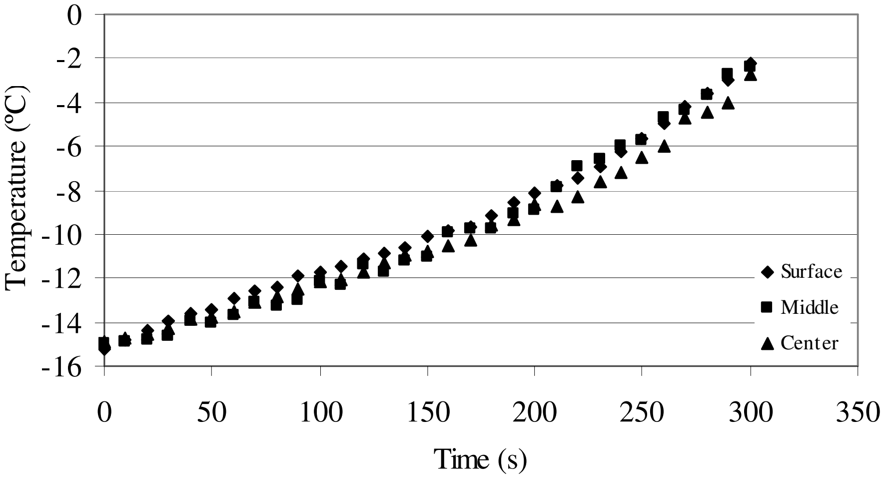

Figure 3.24 Temperature profile of frozen potato puree with 0.75% salt during ohmic tempering at 10 kHz

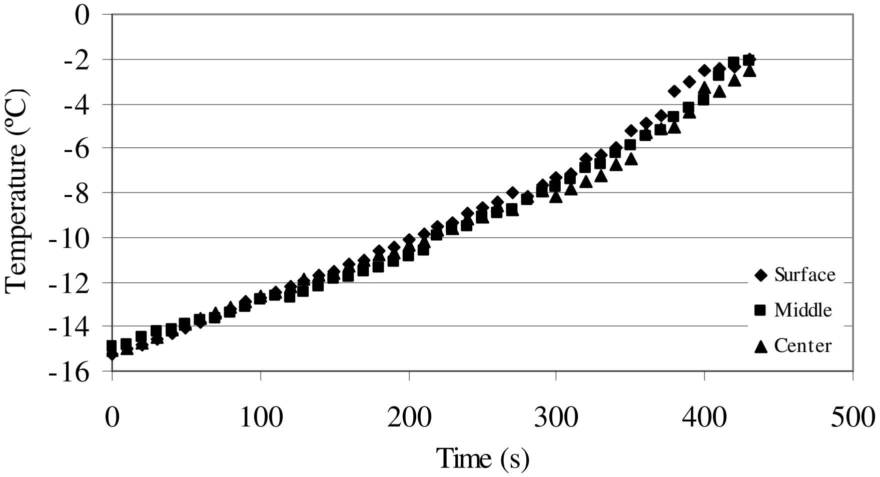

Figure 3.25 Temperature profile of frozen potato puree with 0.50% salt during ohmic tempering at 10 kHz

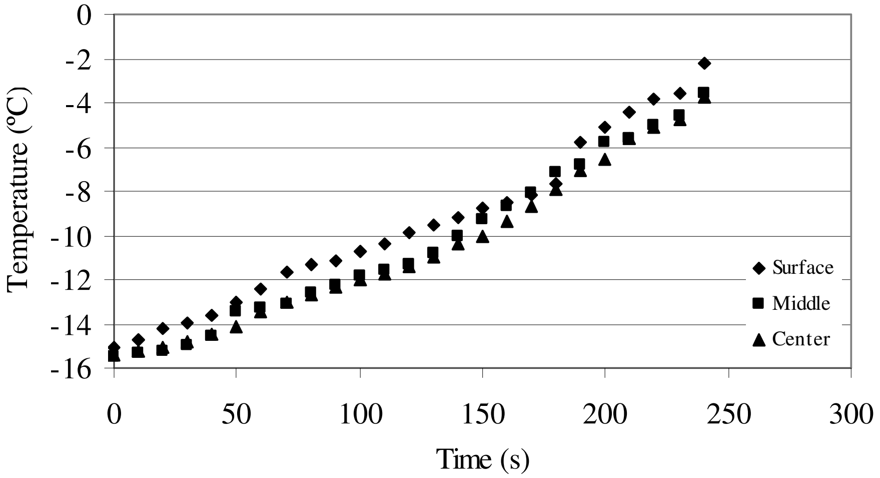

Figure 3.26 Temperature profile of frozen potato puree with 1.00% salt during ohmic tempering at 20 kHz

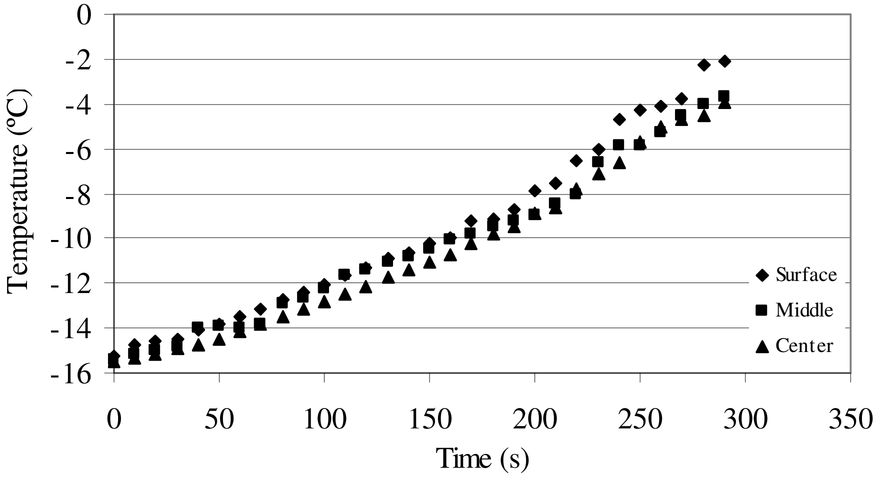

Figure 3.27 Temperature profile of frozen potato puree with 0.75% salt during ohmic tempering at 20 kHz

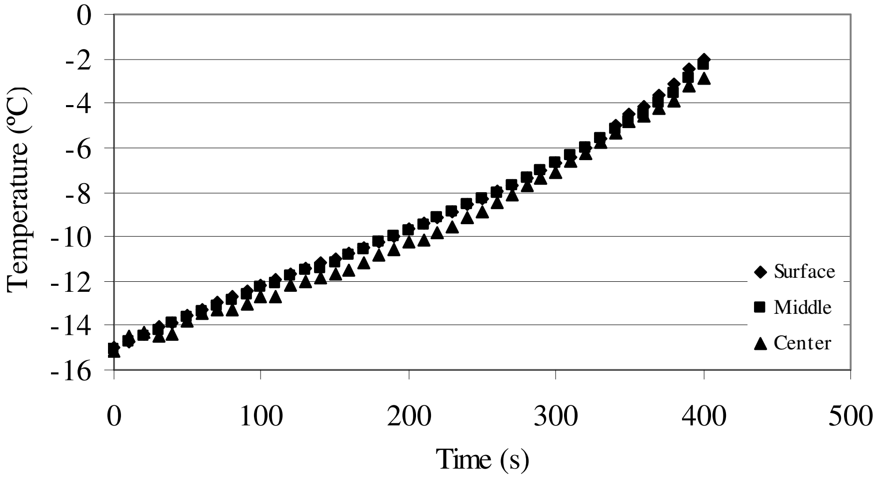

Figure 3.28 Temperature profile of frozen potato puree with 0.50% salt during ohmic tempering at 20 kHz

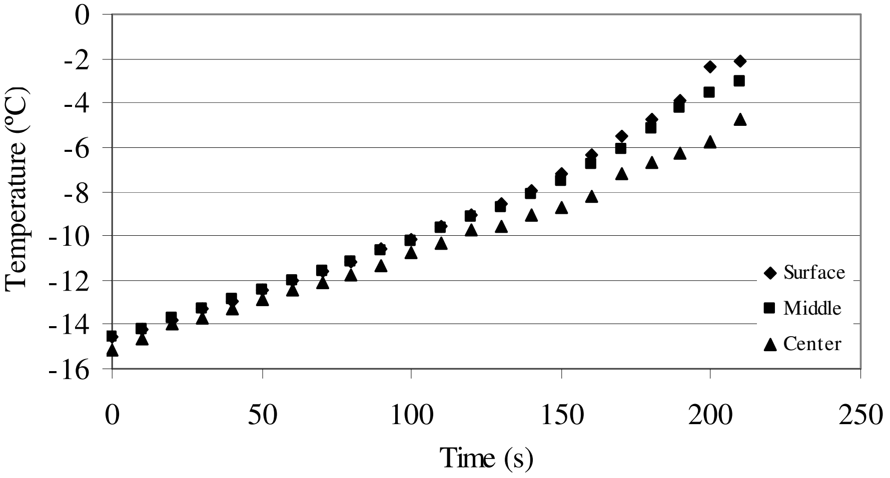

Figure 3.29 Temperature profile of frozen potato puree with 1.00% salt during ohmic tempering at 30 kHz

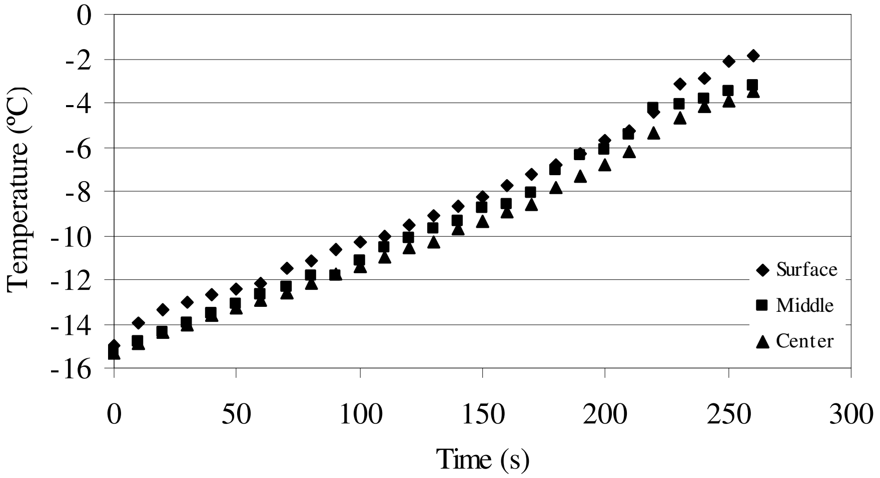

Figure 3.30 Temperature profile of frozen potato puree with 0.75% salt during ohmic tempering at 30 kHz

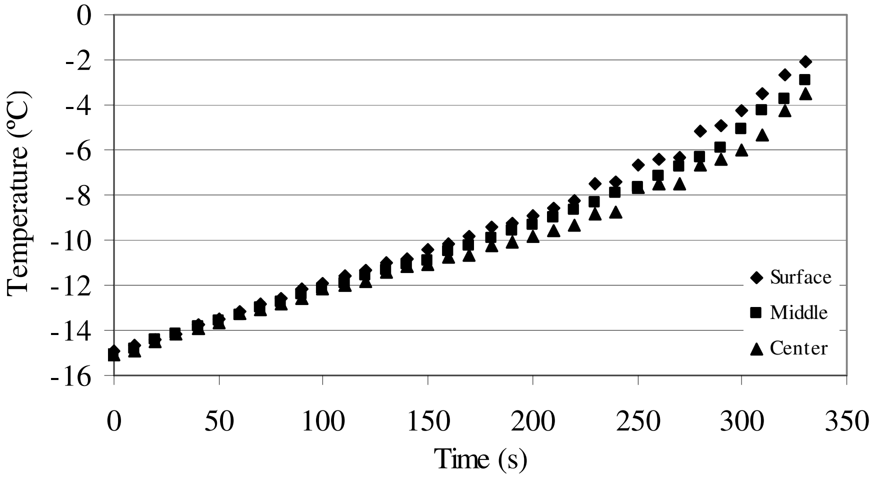

Figure 3.31 Temperature profile of frozen potato puree with 0.50% salt during ohmic tempering at 30 kHz

3.5.1 Effect of Salt Content

Figures 3.32 - 3.34 show the time-temperature profile of ohmic heating with three different salt concentrations. As the salt content of the frozen potato puree sample decreased, the tempering time increased (Figures 3.32 - 3.34). This is because the electrical conductivity of the frozen potato puree decreases by reducing salt content (Figure 3.19). The applicability of ohmic heating is dependent on the product's electrical conductivity, since the amount of heat generated in ohmic heating is directly related to the current induced by the voltage gradient in the field, and the electrical conductivity of the material being heated (Sastry & Li, 1996). Thus, the electrical conductivity of food materials is a critical parameter, and the increase of electrolytic content within foods, which causes high electrical conductivity, can be achieved by salt addition (Figure 3.19). The decrease in the salt content had a decreasing effect on the electrical conductivity of the frozen potato puree samples, resulting in longer tempering times (Figure 3.32 - 3.34).

Increasing the salt content was an effective way of improving the ohmic heating effectiveness, but salt contents more than 1.00% are not preferable for food industries, so salt contents were chosen considering the industrial criteria. In the preliminary studies, 0.25% salt content was also tried for ohmic tempering but at that salt level, it was not possible to observe any current at low temperatures (even at -5ºC). Low salt content can not be a good choice for solid food samples.

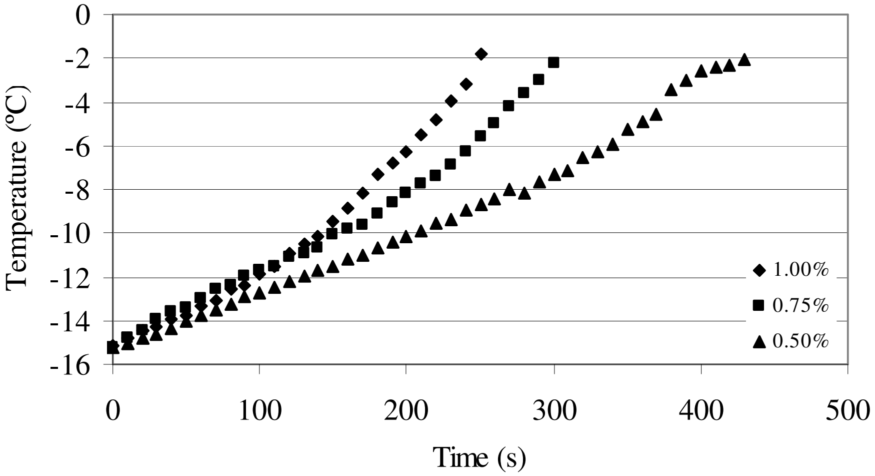

Figure 3.32 Effect of salt content on surface temperature profile of ohmic tempering at 10 kHz

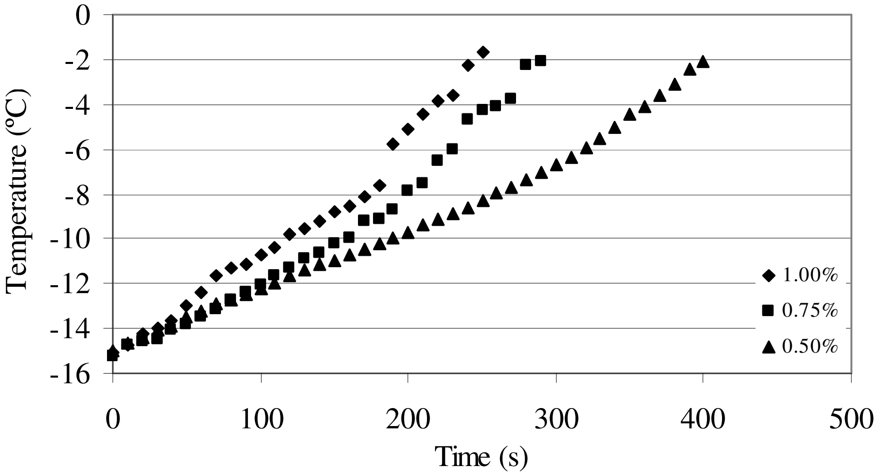

Figure 3.33 Effect of salt content on surface temperature profile of ohmic tempering at 20 kHz

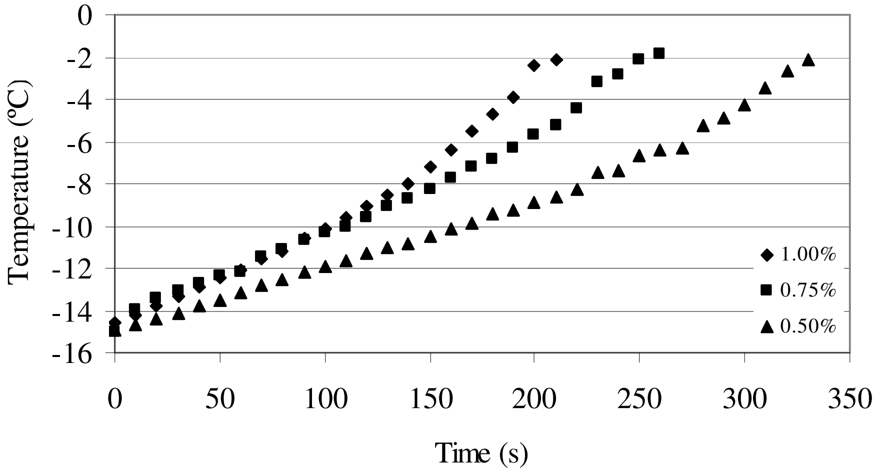

Figure 3.34 Effect of salt content on surface temperature profile of ohmic tempering at 30 kHz

3.5.2 Effect of Frequency

The time-temperature profile of ohmic thawing of potato puree containing different salt contents with three different frequencies is given in Figures 3.35 - 3.37. The temperature values are the ones obtained from the surface probe. As the frequency increased, tempering time decreased. This is because the electrical conductivity also increased by increasing frequency (Figure 3.20) and as a consequence the tempering time decreased.

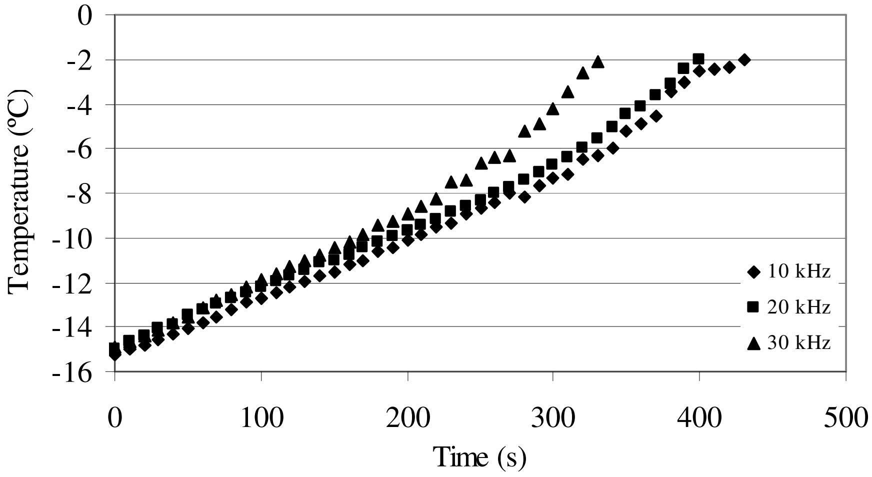

Figure 3.35 Effect of frequency on surface temperature profile during ohmic tempering of frozen potato puree with 0.50% salt

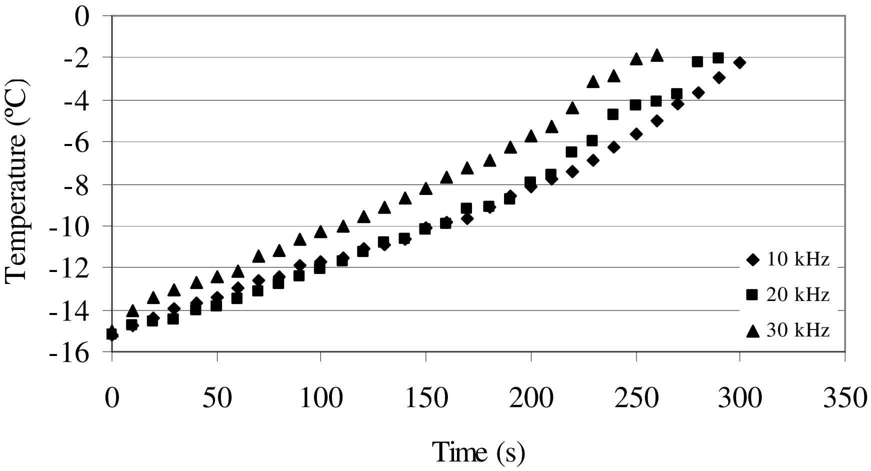

Figure 3.36 Effect of frequency on surface temperature profile during ohmic tempering of frozen potato puree with 0.75% salt

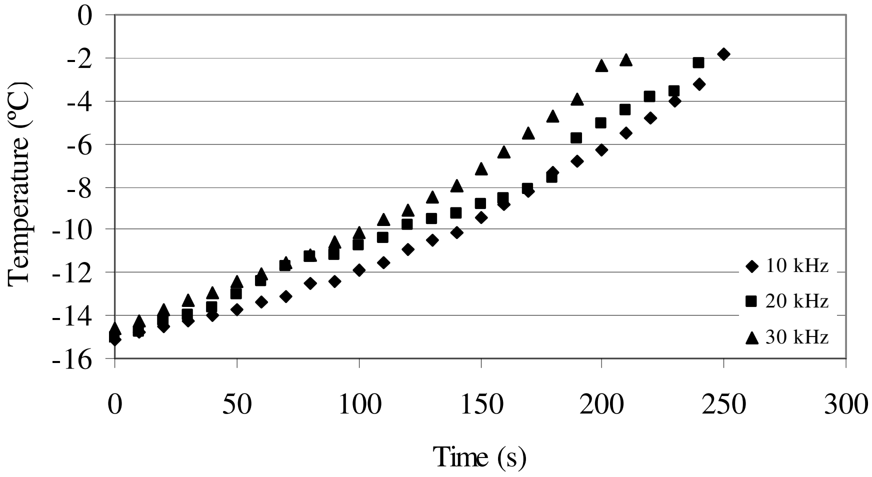

Figure 3.37 Effect of frequency on surface temperature profile during ohmic tempering of frozen potato puree with 1.00% salt

3.6 Conventional Tempering

Conventional tempering experiments of frozen potato puree were performed for two different sample sizes. The conventional tempering took almost 16 hours for frozen potato puree sample with 25 cm diameter and 2.5 cm thickness, and 50 minutes for frozen potato puree sample with 2.5 cm diameter and 3 cm thickness.

CHAPTER 4

CONCLUSION & RECOMMENDATIONS

In this study, microwave tempering, infrared assisted microwave tempering, and ohmic tempering techniques were investigated as alternative tempering methods of frozen foods. All three methods were successful in shortening the tempering time of frozen potato puree significantly.

The temperature distribution and the heating patterns were observed to be different in microwave tempering and infrared assisted microwave tempering. An increase in either microwave power or infrared power resulted in a decrease in tempering time. On the other hand, when microwave power and infrared power were decreased, the temperature profiles of potato puree were more uniform during tempering. Increasing the salt content or frequency decreased the tempering time for frozen potato puree sample in ohmic tempering.

A finite difference model was developed to help to predict the temperature profile of frozen potato puree during microwave tempering and infrared assisted microwave tempering. The models for both microwave tempering and infrared assisted microwave tempering fitted the experimental data well. These models can be used to design microwave tempering and infrared assisted microwave tempering experiments for other frozen foods. These models eliminate the need for preliminary testing, which saves time, money, and resources. A novel tempering technology is introduced by this research. This study will be helpful for further thawing and tempering studies performed with different food samples.

Among different tempering methods, infrared assisted microwave heating at low microwave power (30%) and infrared power (10%) can be recommended since more uniform temperature distribution can be achieved. Ohmic heating had limitations when applied for tempering purposes. The solid state of frozen samples, the need of good contact of the sample with the electrodes, and the electrical conductivity of the sample complicated the ohmic tempering process.

2-D or 3-D modeling of microwave tempering and infrared assisted microwave tempering can be studied as further research. The effect of microwave tempering, infrared assisted microwave tempering, and ohmic tempering on the microbial load of frozen food samples may be studied to obtain the optimum product quality in a further study.

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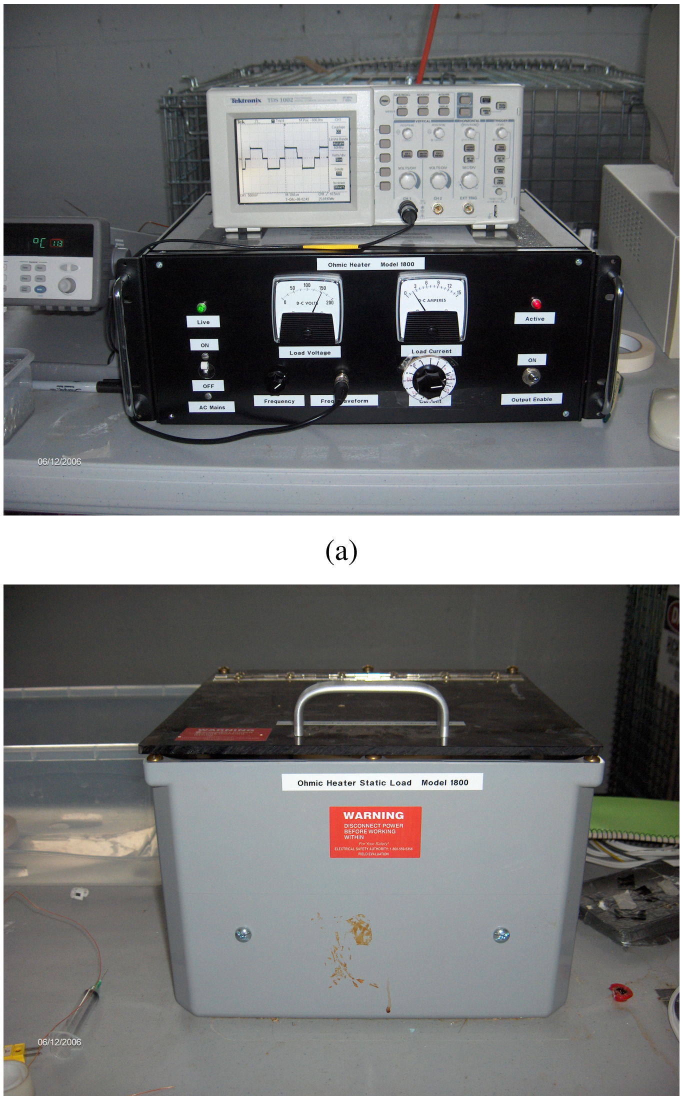
APPENDIX A

Ohmic Heating System



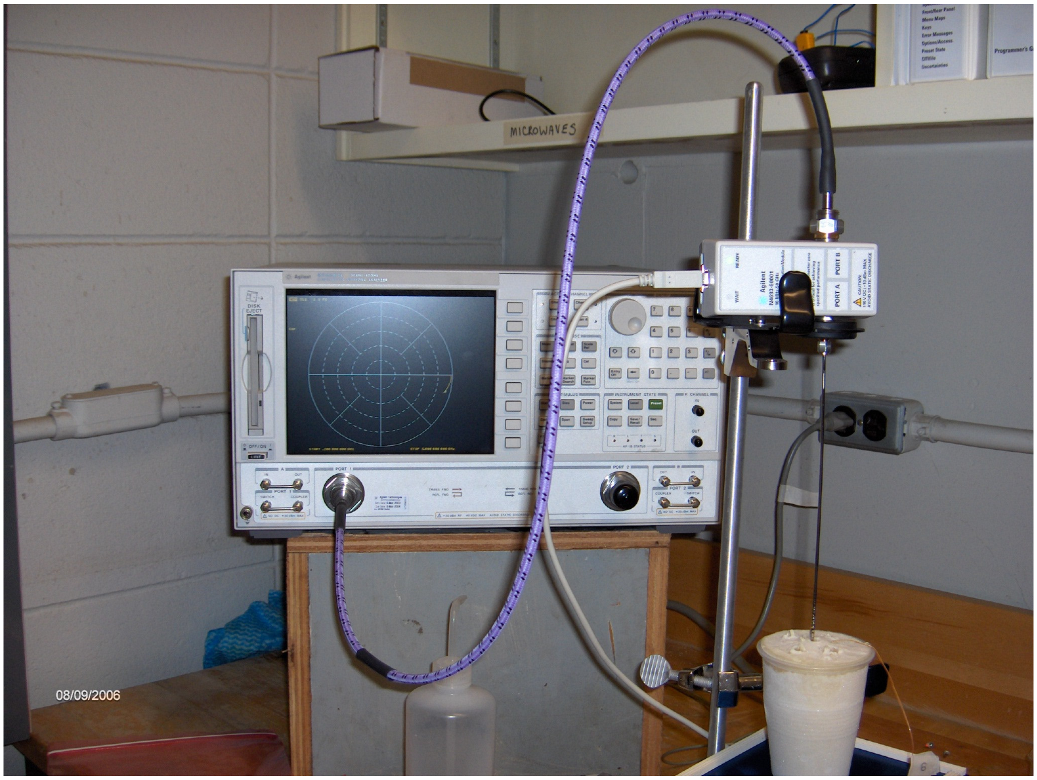
(a)

(b)

Figure A.1 Ohmic heating unit: (a) ohmic heater (b) sample load cell

APPENDIX B

Network Analyzer



08/09/2006

Figure B.1 Network analyzer

APPENDIX C

Measurement of Heat Capacity

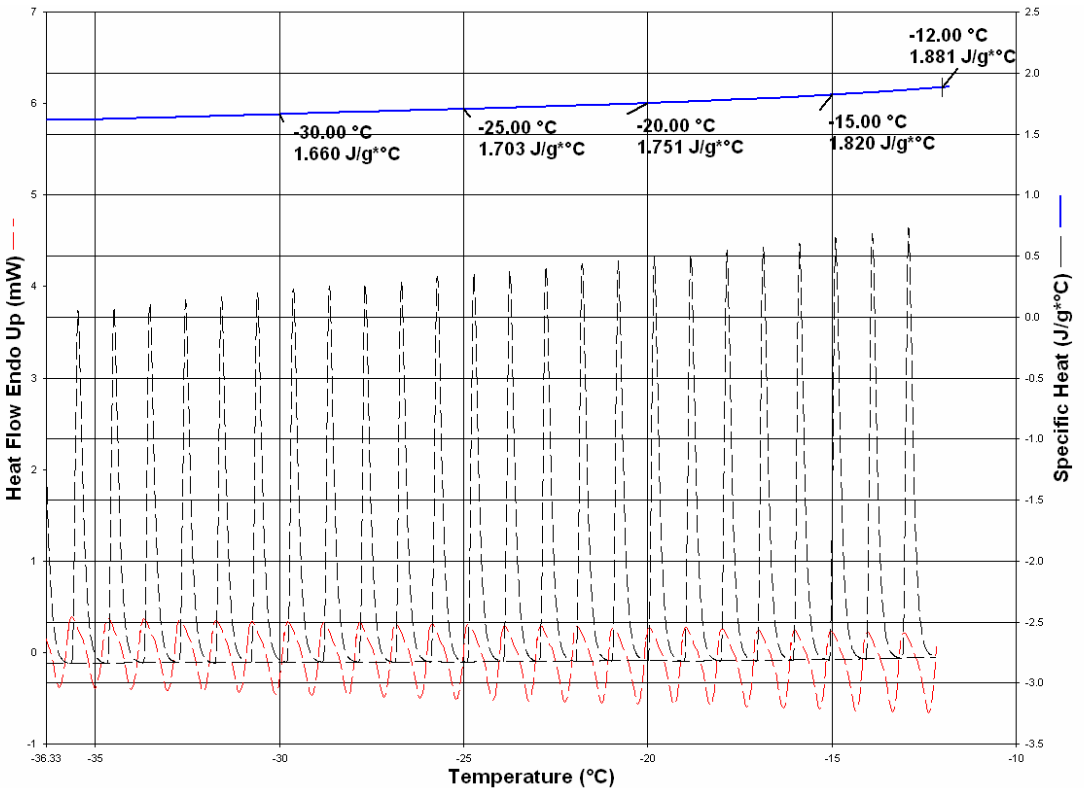


Figure C.1 Change of heat capacity of frozen potato puree with respect to temperature

APPENDIX D

MATLAB Program for Microwave Tempering

```
clear,
To = -25; %initial temperature
N = 26;
L = 0.025; %height of the sample (2.5 cm)
h = 20; %heat transfer coefficient in W/m^2.C
Tinf=20; %ambient temperature
A = 1;

T=To.*ones(1,N); %initial boundary condition

dt=0.0005;

dx=L/(N-1);
x=[0:dx:0.025];

Qo=165000;

for t=0:dt:300
tt=mod(t,10);

if tt==0
  TT(:,A)=T(1:N)';
  A=A+1;
end
```

```
k=((2.01+1.39e-3*T-4.33e-6*T.^2)); %thermal conductivity in W/m.K
dkdT=(1.39e-3-8.66e-6*T);

Cp=2087.8+21.058*T+0.2224*T^2;

ro=1395; %density in kg/m^3

Dp=0.0137+0.0032*T+0.0004*T.^2; %Dp in m

w=1./(ro*Cp);

Q=Qo*exp(-x./Dp);

if t==0
   G=-20;
else
   G=T(2)-2*h*dx*(T(1)-Tinf)/k(1);
end

TN(1)=T(1)+dt*w(1).*(dkdT(1).*((T(2)-G)/(2*dx)).^2+...
   k(1).*((T(2)-2*T(1)+G)/((dx)^2))+Q(1)); %surface boundary condition
T(1)=TN(1);

TN(2:N-1)=T(2:N-1)+dt*w(2:N-1).*(dkdT(2:N-1).*((T(3:N)-T(1:N-
2))/(2*dx)).^2+...
   k(2:N-1).*((T(3:N)-2*T(2:N-1)+T(1:N-2))/((dx)^2))+Q(2:N-1));
T(2:N-1)=TN(2:N-1);

H=T(N);
TN(N)=T(N)+dt*w(N).*(dkdT(N).*((H-T(N-1))/(2*dx)).^2+...
   k(N).*((H-2*T(N)+T(N-1))/(dx)^2)+Q(N)); %insulated boundary condition
```

```
T(N)=TN(N);

end
TT
```

APPENDIX E

Input Parameters

$h = 20$ W/m^2.°C for microwave heating

$h = 30$ W/m^2.°C for infrared assisted microwave heating

$\rho = 1395$ kg/m^3

$D_{p,\,IR} = 3.5$ mm

$$k(T) = 2.01 + 1.39\times10^{-3}\times T - 4.33\times10^{-6}\times T^2$$

$$C_p(T) = 2087.8 + 21.058\times T + 0.2224\times T^2$$

-30ºC < T ≤ -2ºC	$\varepsilon' = 0.1377T^2 + 6.0395T + 65.88$
-2ºC < T ≤ 10ºC	$\varepsilon' = 0.0116T^2 + 0.2573T + 55.645$
-30ºC < T ≤ -8ºC	$\varepsilon'' = 0.0178T^2 + 0.8565T + 10.21$
-8ºC < T ≤ 10ºC	$\varepsilon'' = -0.0838T^2 + 0.5358T + 18.251$

APPENDIX F

MATLAB Program for Infrared Assisted Microwave Tempering

```
clear,
To = -25; %initial temperature
N = 26;
L = 0.025; %height of the sample
h = 30; %heat transfer coefficient
Tinf=20; %ambient temperature
A = 1;

T=To.*ones(1,N); %initial boundary condition
dt=0.0005;
dx=L/(N-1);
x=[0:dx:0.025];

for t=0:dt:240
tt=mod(t,10);

k=(2.01+1.39e-3*T-4.33e-6*T.^2); %thermal conductivity
dkdT=(1.39e-3-8.66e-6*T);

Cp=2087.8+21.058*T+0.2224*T^2;


if tt==0
  TT(:,A)=T(1:N)';
```

```
  A=A+1;
end

ro=1395; %density

Dp=0.0137+0.0032*T+0.0004*T.^2; %Dp in m

w=1./(ro*Cp);

if t==0
   G1=-20;
else
   G1=2*h*dx*(-T(1)+Tinf)/k(1);
end

tp=mod(t,40);
Dph=0.035;

if tp<=7
   Qh=1450000*exp(-x./Dph);

else
   Qh=0;

end

Qo=165000;

Q=Qh+Qo*exp(-x./Dp); %generation term

G=T(2)+G1;
```

```
TN(1)=T(1)+dt*w(1).*(dkdT(1).*((T(2)-G)/(2*dx)).^2+...
   k(1).*((T(2)-2*T(1)+G)/(dx)^2)+Q(1)); %surface boundary condition
T(1)=TN(1);

TN(2:N-1)=T(2:N-1)+dt*w(2:N-1).*(dkdT(2:N-1).*((T(3:N)-T(1:N-
2))/(2*dx)).^2+...
   k(2:N-1).*((T(3:N)-2*T(2:N-1)+T(1:N-2))/(dx)^2)+Q(2:N-1));
T(2:N-1)=TN(2:N-1);

H=T(N);
TN(N)=T(N)+dt*w(N).*(dkdT(N).*((H-T(N-1))/(2*dx)).^2+...
   k(N).*((H-2*T(N)+T(N-1))/(dx)^2)+Q(N)); %insulated boundary condition
T(N)=TN(N);

end
TT
```

APPENDIX G

Two-Way ANOVA Tables for Ohmic Tempering Results

Table G.1 ANOVA for variation of electrical conductivity with salt and temperature at 10 kHz

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	3	0.008545	0.002848	0
Row 2	3	0.011394	0.003798	2.7E-06
Row 3	3	0.014331	0.004777	1.07E-05
Row 4	3	0.022788	0.007596	1.08E-05
Row 5	3	0.030221	0.010074	1.83E-05
Row 6	3	0.038855	0.012952	1.83E-05
Row 7	3	0.051406	0.017135	9.35E-06
Row 8	3	0.071969	0.02399	2.23E-05
Row 9	3	0.126123	0.042041	1.34E-05
Row 10	3	0.206952	0.068984	0.000188
Row 11	3	0.339613	0.113204	8.58E-05
Column 1	11	0.263864	0.023988	0.000988
Column 2	11	0.299932	0.027267	0.001261
Column 3	11	0.358401	0.032582	0.001383

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	0.035977	10	0.003598	208.3728	5.83E-18	2.347875
Columns	0.000414	2	0.000207	11.98435	0.000379	3.492829
Error	0.000345	20	1.73E-05			
Total	0.036737	32				

Table G.2 ANOVA for variation of electrical conductivity with salt and temperature at 20 kHz

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	3	0.011394	0.003798	2.7E-06
Row 2	3	0.016672	0.005557	2.27E-05
Row 3	3	0.028485	0.009495	4.33E-05
Row 4	3	0.038455	0.012818	5.48E-05
Row 5	3	0.045241	0.01508	8.52E-05
Row 6	3	0.05697	0.01899	6.76E-05
Row 7	3	0.069432	0.023144	9.14E-05
Row 8	3	0.091063	0.030354	8.92E-05
Row 9	3	0.128773	0.042924	0.000132
Row 10	3	0.242581	0.08086	0.000306
Row 11	3	0.377213	0.125738	0.000138
Column 1	11	0.287014	0.026092	0.001096
Column 2	11	0.357363	0.032488	0.001752
Column 3	11	0.4619	0.041991	0.001471

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	0.042521	10	0.004252	128.8108	6.61E-16	2.347875
Columns	0.001408	2	0.000704	21.32612	1.1E-05	3.492829
Error	0.00066	20	3.3E-05			
Total	0.044589	32				

Table G.3 ANOVA for variation of electrical conductivity with salt and temperature at 30 kHz

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	3	0.014242	0.004747	1.08E-05
Row 2	3	0.026212	0.008737	1.35E-05
Row 3	3	0.039879	0.013293	6.76E-05
Row 4	3	0.047	0.015667	7.51E-05
Row 5	3	0.054121	0.01804	8.38E-05
Row 6	3	0.074364	0.024788	7.52E-05
Row 7	3	0.092188	0.030729	0.000146
Row 8	3	0.111625	0.037208	0.000141
Row 9	3	0.168815	0.056272	0.000352
Row 10	3	0.282714	0.094238	0.000494
Row 11	3	0.454839	0.151613	0.000919
Column 1	11	0.329965	0.029997	0.001276
Column 2	11	0.440869	0.040079	0.002175
Column 3	11	0.595164	0.054106	0.002695

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	0.059926	10	0.005993	78.30546	8.39E-14	2.347875
Columns	0.003225	2	0.001613	21.07296	1.19E-05	3.492829
Error	0.001531	20	7.65E-05			
Total	0.064682	32				

Table G.4 ANOVA for variation of temperature at different positions during ohmic tempering at 10 kHz for 1% salt

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	3	-44.482	-14.8273	0.067685
Row 2	3	-43.568	-14.5227	0.065284
Row 3	3	-42.811	-14.2703	0.033385
Row 4	3	-41.853	-13.951	0.089563
Row 5	3	-40.836	-13.612	0.094012
Row 6	3	-40.581	-13.527	0.041875
Row 7	3	-39.415	-13.1383	0.059269
Row 8	3	-38.155	-12.7183	0.177012
Row 9	3	-37.393	-12.4643	0.028564
Row 10	3	-36.617	-12.2057	0.05689
Row 11	3	-34.841	-11.6137	0.090645
Row 12	3	-33.541	-11.1803	0.287801
Row 13	3	-32.161	-10.7203	0.252386
Row 14	3	-31.472	-10.4907	0.000321
Row 15	3	-29.133	-9.711	0.181459
Row 16	3	-28.084	-9.36133	0.329926
Row 17	3	-26.933	-8.97767	0.382126
Row 18	3	-24.707	-8.23567	0.017801
Row 19	3	-22.975	-7.65833	0.625252
Row 20	3	-20.389	-6.79633	0.001792
Row 21	3	-18.735	-6.245	0.001519
Row 22	3	-16.264	-5.42133	0.151637
Row 23	3	-14.323	-4.77433	0.027556
Row 24	3	-10.456	-3.48533	0.185152
Row 25	3	-9.086	-3.02867	0.028245
Row 26	3	-5.692	-1.89733	0.002552
Row 27	3	-0.213	-0.071	11.4241
Column 1	27	-255.213	-9.45233	22.07001
Column 2	27	-250.443	-9.27567	16.10071
Column 3	27	-259.06	-9.59481	16.63392

Table G.4 ANOVA for variation of temperature at different positions during ohmic tempering at 10 kHz for 1% salt (continued)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	1396.893	26	53.72667	99.6808	9.36E-36	1.709619
Columns	1.380309	2	0.690154	1.280465	0.286524	3.175145
Error	28.02733	52	0.538987			
Total	1426.301	80				

Table G.5 ANOVA for variation of temperature at different positions during ohmic tempering at 10 kHz for 0.75% salt

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	3	-45.056	-15.0187	0.028881
Row 2	3	-44.414	-14.8047	0.009494
Row 3	3	-43.814	-14.6047	0.045874
Row 4	3	-42.768	-14.256	0.117111
Row 5	3	-41.495	-13.8317	0.030442
Row 6	3	-41.175	-13.725	0.081372
Row 7	3	-40.163	-13.3877	0.15709
Row 8	3	-38.747	-12.9157	0.081512
Row 9	3	-38.45	-12.8167	0.166902
Row 10	3	-37.423	-12.4743	0.287681
Row 11	3	-36.009	-12.003	0.060199
Row 12	3	-35.87	-11.9567	0.182854
Row 13	3	-34.229	-11.4097	0.10738
Row 14	3	-33.934	-11.3113	0.18281
Row 15	3	-32.856	-10.952	0.092383
Row 16	3	-31.976	-10.6587	0.252984
Row 17	3	-30.254	-10.0847	0.147676
Row 18	3	-29.629	-9.87633	0.12702
Row 19	3	-28.462	-9.48733	0.090386
Row 20	3	-26.986	-8.99533	0.154246
Row 21	3	-25.731	-8.577	0.151644

Table G.5 ANOVA for variation of temperature at different positions during ohmic tempering at 10 kHz for 0.75% salt (continued)

Row 22	3	-24.418	-8.13933	0.300241
Row 23	3	-22.63	-7.54333	0.457701
Row 24	3	-21.146	-7.04867	0.294584
Row 25	3	-19.499	-6.49967	0.387649
Row 26	3	-17.803	-5.93433	0.216165
Row 27	3	-15.757	-5.25233	0.457734
Row 28	3	-13.315	-4.43833	0.077929
Row 29	3	-11.803	-3.93433	0.216165
Row 30	3	-9.757	-3.25233	0.457734
Row 31	3	-7.315	-2.43833	0.077929
Column 1	31	-298.545	-9.63048	13.58734
Column 2	31	-308.644	-9.95626	15.24747
Column 3	31	-315.695	-10.1837	11.98892

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	1218.506	30	40.61687	392.7053	1.49E-58	1.64914
Columns	4.793859	2	2.39693	2.317478	3.49E-08	3.15041
Error	6.205702	60	0.103428			
Total	1229.506	92				

Table G.6 ANOVA for variation of temperature at different positions during ohmic tempering at 10 kHz for 0.5% salt

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	3	-45.225	-15.075	0.024528
Row 2	3	-44.82	-14.94	0.010192
Row 3	3	-44.066	-14.6887	0.025836
Row 4	3	-43.247	-14.4157	0.044356
Row 5	3	-42.711	-14.237	0.008593

Table G.6 ANOVA for variation of temperature at different positions during ohmic tempering at 10 kHz for 0.5% salt (continued)

Row 6	3	-41.788	-13.9293	0.007534
Row 7	3	-41.159	-13.7197	0.00696
Row 8	3	-40.542	-13.514	0.011149
Row 9	3	-39.68	-13.2267	0.016072
Row 10	3	-38.872	-12.9573	0.017577
Row 11	3	-38.231	-12.7437	0.00783
Row 12	3	-37.519	-12.5063	0.01466
Row 13	3	-37.192	-12.3973	0.07379
Row 14	3	-36.23	-12.0767	0.090921
Row 15	3	-35.637	-11.879	0.092197
Row 16	3	-34.988	-11.6627	0.030284
Row 17	3	-34.292	-11.4307	0.111116
Row 18	3	-33.603	-11.201	0.093328
Row 19	3	-32.776	-10.9253	0.165072
Row 20	3	-32.199	-10.733	0.124524
Row 21	3	-31.336	-10.4453	0.128008
Row 22	3	-30.675	-10.225	0.159484
Row 23	3	-29.137	-9.71233	0.037381
Row 24	3	-28.519	-9.50633	0.018074
Row 25	3	-27.594	-9.198	0.092071
Row 26	3	-26.906	-8.96867	0.071926
Row 27	3	-25.982	-8.66067	0.07763
Row 28	3	-25.52	-8.50667	0.18076
Row 29	3	-24.586	-8.19533	0.009076
Row 30	3	-23.51	-7.83667	0.022514
Row 31	3	-23.19	-7.73	0.165676
Row 32	3	-22.38	-7.46	0.110784
Row 33	3	-20.859	-6.953	0.245739
Row 34	3	-20.267	-6.75567	0.21235
Row 35	3	-18.891	-6.297	0.144021
Row 36	3	-17.603	-5.86767	0.388462
Row 37	3	-15.645	-5.215	0.089404
Row 38	3	-14.868	-4.956	0.125569
Row 39	3	-13.172	-4.39067	0.7061

Table G.6 ANOVA for variation of temperature at different positions during ohmic tempering at 10 kHz for 0.5% salt (continued)

Row 40	3	-11.55	-3.85	0.523033
Row 41	3	-9.701	-3.23367	0.43378
Row 42	3	-8.645	-2.88167	0.269289
Row 43	3	-7.539	-2.513	0.165676
Row 44	3	-6.651	-2.217	0.090228
Column 1	44	-409.674	-9.31077	15.56243
Column 2	44	-425.78	-9.67682	13.98372
Column 3	44	-424.049	-9.63748	12.71749

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	1810.002	43	42.09308	493.6063	2.47E-87	1.521821
Columns	3.553335	2	1.776668	20.83417	4.19E-08	3.102556
Error	7.33379	86	0.085277			
Total	1820.89	131				

Table G.7 ANOVA for variation of temperature at different positions during ohmic tempering at 20 kHz for 1% salt

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	3	-45.949	-15.3163	0.050676
Row 2	3	-45.36	-15.12	0.098881
Row 3	3	-44.515	-14.8383	0.284534
Row 4	3	-43.743	-14.581	0.305956
Row 5	3	-42.635	-14.2117	0.256601
Row 6	3	-40.646	-13.5487	0.325862
Row 7	3	-39.068	-13.0227	0.307746
Row 8	3	-37.815	-12.605	0.637644
Row 9	3	-36.568	-12.1893	0.589084
Row 10	3	-35.74	-11.9133	0.434289

Table G.7 ANOVA for variation of temperature at different positions during ohmic tempering at 20 kHz for 1% salt (continued)

Row 11	3	-34.536	-11.512	0.468844
Row 12	3	-33.768	-11.256	0.570099
Row 13	3	-32.518	-10.8393	0.757326
Row 14	3	-31.337	-10.4457	0.594206
Row 15	3	-29.609	-9.86967	0.342842
Row 16	3	-28.16	-9.38667	0.389314
Row 17	3	-26.556	-8.852	0.172732
Row 18	3	-24.912	-8.304	0.1225
Row 19	3	-22.751	-7.58367	0.154746
Row 20	3	-19.59	-6.53	0.460804
Row 21	3	-17.456	-5.81867	0.509796
Row 22	3	-15.647	-5.21567	0.45155
Row 23	3	-14.015	-4.67167	0.49232
Row 24	3	-12.995	-4.33167	0.395409
Row 25	3	-9.519	-3.173	0.645109
Row 26	3	-7.139	-2.37967	0.508649
Column 1	26	-240.739	-9.25919	15.85258
Column 2	26	-262.754	-10.1059	15.90482
Column 3	26	-269.054	-10.3482	14.72663

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	1158.447	25	46.33787	634.0874	2.81E-54	1.727344
Columns	17.00115	2	8.500573	116.3218	1.56E-19	3.182606
Error	3.653903	50	0.073078			
Total	1179.102	77				

Table G.8 ANOVA for variation of temperature at different positions during ohmic tempering at 20 kHz for 0.75% salt

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	3	-46.108	-15.3693	0.02577
Row 2	3	-45.237	-15.079	0.079267
Row 3	3	-44.688	-14.896	0.103111
Row 4	3	-44.296	-14.7653	0.050946
Row 5	3	-42.806	-14.2687	0.1709
Row 6	3	-42.197	-14.0657	0.119932
Row 7	3	-41.625	-13.875	0.110596
Row 8	3	-40.728	-13.576	0.153628
Row 9	3	-39.207	-13.069	0.154233
Row 10	3	-38.223	-12.741	0.133321
Row 11	3	-37.102	-12.3673	0.150752
Row 12	3	-35.758	-11.9193	0.211326
Row 13	3	-34.81	-11.6033	0.23298
Row 14	3	-33.653	-11.2177	0.228076
Row 15	3	-32.847	-10.949	0.154375
Row 16	3	-31.759	-10.5863	0.18943
Row 17	3	-30.683	-10.2277	0.166609
Row 18	3	-29.257	-9.75233	0.25827
Row 19	3	-28.412	-9.47067	0.129362
Row 20	3	-27.423	-9.141	0.144937
Row 21	3	-25.687	-8.56233	0.318532
Row 22	3	-24.689	-8.22967	0.324
Row 23	3	-22.392	-7.464	0.698713
Row 24	3	-19.699	-6.56633	0.313614
Row 25	3	-17.184	-5.728	0.907417
Row 26	3	-15.846	-5.282	0.790447
Row 27	3	-14.469	-4.823	0.399639
Row 28	3	-12.939	-4.313	0.218071
Row 29	3	-10.815	-3.605	1.395984
Row 30	3	-9.721	-3.24033	1.04001
Column 1	30	-291.681	-9.7227	15.99427
Column 2	30	-309.029	-10.301	12.78045
Column 3	30	-319.55	-10.6517	13.27711

Table G.8 ANOVA for variation of temperature at different positions during ohmic tempering at 20 kHz for 0.75% salt (continued)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	1213.958	29	41.86063	437.8658	5.02E-58	1.662901
Columns	13.20362	2	6.601809	69.05549	4.54E-16	3.155932
Error	5.544888	58	0.095602			
Total	1232.707	89				

Table G.9 ANOVA for variation of temperature at different positions during ohmic tempering at 20 kHz for 0.5% salt

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	3	-45.153	-15.051	0.004507
Row 2	3	-43.934	-14.6447	0.01613
Row 3	3	-43.086	-14.362	0.008137
Row 4	3	-42.784	-14.2613	0.046664
Row 5	3	-42.18	-14.06	0.093499
Row 6	3	-40.907	-13.6357	0.016794
Row 7	3	-40.083	-13.361	0.012564
Row 8	3	-39.332	-13.1107	0.032764
Row 9	3	-38.874	-12.958	0.107968
Row 10	3	-38.143	-12.7143	0.093982
Row 11	3	-37.234	-12.4113	0.075342
Row 12	3	-36.775	-12.2583	0.170585
Row 13	3	-35.697	-11.899	0.082828
Row 14	3	-34.996	-11.6653	0.099506
Row 15	3	-34.414	-11.4713	0.142604
Row 16	3	-33.843	-11.281	0.128772
Row 17	3	-33.016	-11.0053	0.172682
Row 18	3	-32.16	-10.72	0.129819
Row 19	3	-31.318	-10.4393	0.124762
Row 20	3	-30.56	-10.1867	0.122526

Table G.9 ANOVA for variation of temperature at different positions during ohmic tempering at 20 kHz for 0.5% salt (continued)

Row 21	3	-29.667	-9.889	0.108073
Row 22	3	-29.023	-9.67433	0.184536
Row 23	3	-28.14	-9.38	0.134437
Row 24	3	-27.313	-9.10433	0.138532
Row 25	3	-26.31	-8.77	0.101037
Row 26	3	-25.425	-8.475	0.106669
Row 27	3	-24.489	-8.163	0.072723
Row 28	3	-23.579	-7.85967	0.060164
Row 29	3	-22.477	-7.49233	0.037189
Row 30	3	-21.454	-7.15133	0.035865
Row 31	3	-20.491	-6.83033	0.043814
Row 32	3	-19.371	-6.457	0.011053
Row 33	3	-18.252	-6.084	0.022932
Row 34	3	-16.868	-5.62267	0.007345
Row 35	3	-15.541	-5.18033	0.02003
Row 36	3	-14.125	-4.70833	0.040912
Row 37	3	-13.192	-4.39733	0.05751
Row 38	3	-11.78	-3.92667	0.091184
Row 39	3	-10.532	-3.51067	0.138054
Row 40	3	-8.54	-2.84667	0.142689
Row 41	3	-7.248	-2.416	0.171748
Column 1	41	-381.353	-9.30129	13.22513
Column 2	41	-385.93	-9.41293	12.85063
Column 3	41	-401.023	-9.78105	12.85361

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	1555.525	40	38.88812	1885.553	1.4E-104	1.544887
Columns	5.167939	2	2.583969	125.2879	2.25E-25	3.11077
Error	1.64994	80	0.020624			
Total	1562.343	122				

Table G.10 ANOVA for variation of temperature at different positions during ohmic tempering at 30 kHz for 1% salt

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	3	-44.265	-14.755	0.107227
Row 2	3	-43.084	-14.3613	0.072192
Row 3	3	-41.482	-13.8273	0.012841
Row 4	3	-40.316	-13.4387	0.043706
Row 5	3	-39.095	-13.0317	0.059642
Row 6	3	-37.732	-12.5773	0.048302
Row 7	3	-36.529	-12.1763	0.05948
Row 8	3	-35.279	-11.7597	0.107924
Row 9	3	-34.065	-11.355	0.105625
Row 10	3	-32.634	-10.878	0.173413
Row 11	3	-31.096	-10.3653	0.090358
Row 12	3	-29.548	-9.84933	0.15287
Row 13	3	-27.993	-9.331	0.145579
Row 14	3	-26.736	-8.912	0.297259
Row 15	3	-25.139	-8.37967	0.358545
Row 16	3	-23.441	-7.81367	0.698326
Row 17	3	-21.393	-7.131	0.905764
Row 18	3	-18.77	-6.25667	0.737146
Row 19	3	-16.511	-5.50367	1.049162
Row 20	3	-14.451	-4.817	1.649977
Row 21	3	-11.716	-3.90533	2.93277
Row 22	3	-9.939	-3.313	1.826877
Column 1	22	-204.092	-9.27691	14.75495
Column 2	22	-208.857	-9.4935	12.57413
Column 3	22	-228.265	-10.3757	9.208316

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	758.92	21	36.13905	181.445	1.41E-34	1.812818
Columns	14.90469	2	7.452346	37.41635	4.67E-10	3.219938
Error	8.365288	42	0.199174			
Total	782.19	65				

Table G.11 ANOVA for variation of temperature at different positions during ohmic tempering at 30 kHz for 0.75% salt

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	3	-45.621	-15.207	0.032137
Row 2	3	-43.713	-14.571	0.249787
Row 3	3	-42.19	-14.0633	0.350532
Row 4	3	-41.061	-13.687	0.312348
Row 5	3	-39.861	-13.287	0.257124
Row 6	3	-38.764	-12.9213	0.216841
Row 7	3	-37.808	-12.6027	0.157777
Row 8	3	-36.396	-12.132	0.348543
Row 9	3	-35.139	-11.713	0.255501
Row 10	3	-34.248	-11.416	0.427237
Row 11	3	-32.889	-10.963	0.342657
Row 12	3	-31.534	-10.5113	0.21658
Row 13	3	-30.212	-10.0707	0.22476
Row 14	3	-29.018	-9.67267	0.341057
Row 15	3	-27.764	-9.25467	0.282117
Row 16	3	-26.384	-8.79467	0.286944
Row 17	3	-25.298	-8.43267	0.4155
Row 18	3	-23.875	-7.95833	0.48476
Row 19	3	-21.729	-7.243	0.270859
Row 20	3	-19.998	-6.666	0.325056
Row 21	3	-18.585	-6.195	0.294319
Row 22	3	-16.9	-5.63333	0.23752
Row 23	3	-14.027	-4.67567	0.37586
Row 24	3	-11.919	-3.973	0.561541
Row 25	3	-10.86	-3.62	0.474663
Row 26	3	-9.571	-3.19033	0.93806
Row 27	3	-8.6	-2.86667	0.780712
Column 1	27	-235.313	-8.7153	14.61396
Column 2	27	-254.112	-9.41156	14.58969
Column 3	27	-264.539	-9.79774	13.08569

Table G.11 ANOVA for variation of temperature at different positions during ohmic tempering at 30 kHz for 0.75% salt (continued)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	1096.852	26	42.1866	821.25	2.78E-59	1.709619
Columns	16.25042	2	8.125209	158.1741	7.82E-23	3.175145
Error	2.671176	52	0.051369			
Total	1115.773	80				

Table G.12 ANOVA for variation of temperature at different positions during ohmic tempering at 30 kHz for 0.5% salt

SUMMARY	*Count*	*Sum*	*Average*	*Variance*
Row 1	3	-45.065	-15.0217	0.010392
Row 2	3	-44.323	-14.7743	0.014702
Row 3	3	-43.33	-14.4433	0.001641
Row 4	3	-42.475	-14.1583	0.001733
Row 5	3	-41.534	-13.8447	0.002866
Row 6	3	-40.819	-13.6063	0.007002
Row 7	3	-39.676	-13.2253	0.004622
Row 8	3	-38.862	-12.954	0.011668
Row 9	3	-38.188	-12.7293	0.022142
Row 10	3	-37.207	-12.4023	0.042457
Row 11	3	-36.228	-12.076	0.022672
Row 12	3	-35.502	-11.834	0.036379
Row 13	3	-34.742	-11.5807	0.076794
Row 14	3	-33.766	-11.2553	0.040556
Row 15	3	-33.048	-11.016	0.032473
Row 16	3	-32.384	-10.7947	0.09344
Row 17	3	-31.465	-10.4883	0.09479
Row 18	3	-30.772	-10.2573	0.177194
Row 19	3	-29.641	-9.88033	0.17958
Row 20	3	-28.946	-9.64867	0.184792
Row 21	3	-28.061	-9.35367	0.217184
Row 22	3	-27.229	-9.07633	0.250137

Table G.12 ANOVA for variation of temperature at different positions during ohmic tempering at 30 kHz for 0.5% salt (continued)

Row 23	3	-26.255	-8.75167	0.322146
Row 24	3	-24.622	-8.20733	0.449726
Row 25	3	-24.061	-8.02033	0.466454
Row 26	3	-21.912	-7.304	0.333823
Row 27	3	-21.092	-7.03067	0.315137
Row 28	3	-20.543	-6.84767	0.360294
Row 29	3	-18.15	-6.05	0.563407
Row 30	3	-17.289	-5.763	0.650748
Row 31	3	-15.298	-5.09933	0.777486
Row 32	3	-13.106	-4.36867	0.850004
Row 33	3	-10.676	-3.55867	0.670785
Row 34	3	-8.573	-2.85767	0.510376
Column 1	34	-324.516	-9.54459	13.3442
Column 2	34	-339.805	-9.99426	11.2835
Column 3	34	-350.519	-10.3094	9.787705

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	1130.163	33	34.24737	407.6222	9.49E-65	1.612216
Columns	10.04607	2	5.023036	59.78564	1.53E-15	3.135924
Error	5.54515	66	0.084017			
Total	1145.754	101				

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EDUCATION

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B.S.	M.E.T.U., Food Engineering, Ankara	1999
High School	Trabzon Yomra Fen Lisesi, Trabzon	1994
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WORK EXPERIENCE

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2002 - present	M.E.T.U., Department of Food Engineering	Research Assistant
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FOREIGN LANGUAGES

English: Advanced, **French**: Beginner

THESES

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1. **Seyhun, N.**, Sumnu, G. & Sahin, S., "Effects of Different Starch Types on Retardation of Staling of Microwave-baked Cakes", *Foods & Bioproducts Processing,* 83, 1-5, 2005.

2. **Seyhun, N.**, Şümnü, G. & Şahin, S., "Farklı Nişasta ve Emülgatör Çeşitlerinin ve Yağ Miktarlarının Mikrodalga ile Pişirilen Keklerin Bayatlaması Üzerindeki Etkileri", *Gıda*, 29 (5), 337-343, 2004.

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5. **Seyhun, N.,** Sumnu, G. & Sahin, S., "Usage of Gums for Retardation of Staling of Microwave Baked Cakes", Poster presentation in 9th International Conference on Microwave and High Frequency Heating, Loughborough University, Loughborough, England, September 2003.